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Natural removal of pollution from the atmosphere

By A. R. MEETHAM
National Physical Laboratory

(Manuscript received 2 January 1950)*

SUMMARY

Observations of atmospheric pollution throughout Britain are considered in relation to the amounts of pollution emitted through the combustion of coal. The estimated weight of ash emitted into the air and the estimate, from deposit gauges, of the ash deposited, are considered likely to agree fairly well at a figure of rather over one million tons per annum (one million tonnes/yr).

On the assumption that about 1·5 million tons of smoke are blown to sea each year, it is shown that about 1·1 million tons of sulphur dioxide are blown to sea each year ; the remaining 0·8 million tons of smoke and 3·9 million tons of sulphur dioxide must be deposited in Britain, irrespective of the quantities measured in deposit gauges.

The average life of a smoke particle before deposition on land is probably of the order of 1-2 days ; that of a molecule of sulphur dioxide is estimated with rather more certainty to be less than 12 hours.

Of the chlorides collected in deposit gauges more than half, as a rule, come from the sea, and less than half from the utilization of coal ; but the ratio must vary with the position of the deposit gauge relative to the sea and to industries.

1. Deposited pollution compared with that emitted

Under the guidance of the Department of Scientific and Industrial Research, a number of local authorities and others have for many years been making systematic observations of atmospheric pollution, rather like climatological records. These include numerous observations with the *deposit gauge*, a large glass raingauge, diameter 12 in., height 4ft 6in., which is emptied for analysis every month. The analysis includes an estimate of the rainfall (which agrees remarkably well with the monthly total from standard raingauges) and estimates of the rate of deposit of different forms of atmospheric pollution, some dissolved in the rain water, and some undissolved. The latest report containing these observations is entitled "Investigation of Atmospheric Pollution, 5 years ended 31st March, 1944, 26th Report" ; it was published in 1949 by H.M. Stationery Office.

In Appendix VI of the 26th Report there is a reprint of Dr. A. Parker's Chadwick Public Lecture of 1945 entitled "Coal in Relation to Atmospheric Pollution", and this contains a table of estimates of the total emission of atmospheric pollution in Britain from the burning and other utilization of coal. So, in one volume are given amounts of pollution both emitted and found, and it is obviously important to study the agreement or disagreement of the two sets of figures.

* Based on a lecture "Physics of Atmospheric Pollution" given at a joint meeting of the Royal Meteorological Society and the Institute of Physics (London and Home Counties Branch) on 23 November 1949. The author is indebted to several persons who took part in the subsequent discussion, for suggestions which have been used in preparing this paper.

Figure 1. Ash.

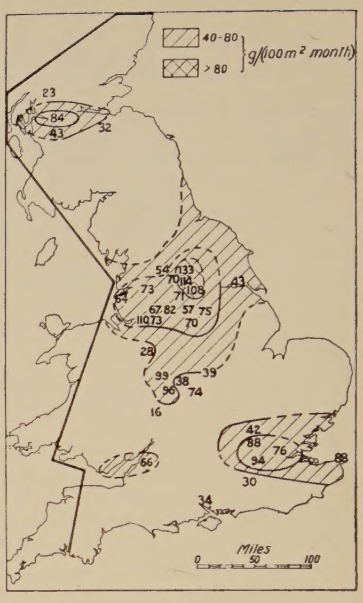


Figure 2. Combustible matter.

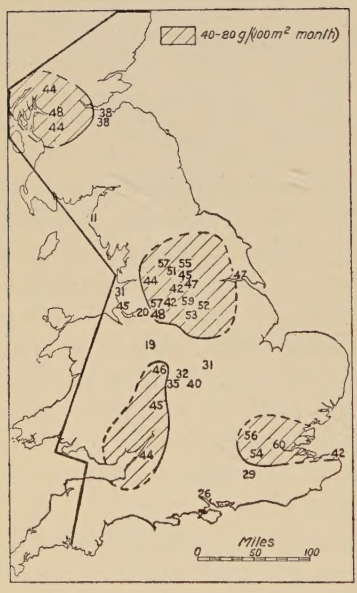


Figure 3. Sulphates.

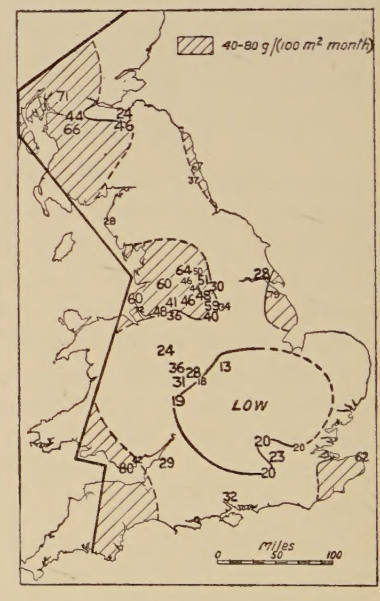


Figure 4. Chlorides.

Figures 1 — 4. Pollution deposited in country districts, g/(100m² mth). (× 0·306 to equal tons mi^{-2} yr^{-1}). In Fig. 4 small numerals are used to indicate sites, where the ash deposit, treated as an index of pollution from coal, exceeds 120 g/(100m² mth).

Figs. 1 — 4 represent the amounts of different substances collected by deposit gauges in country districts. The substances are *ash* and *combustible matter*, which together make up the undissolved matter found in deposit gauges, and *sulphates* and *chlorides* found dissolved in the rain water. The quantity of sulphate is expressed as the equivalent weight of sulphur dioxide, since this is by far the commonest compound of sulphur in chimney gases. The deposits are recorded in g/(100m² mth).

To be representative of country districts, deposit gauges were chosen, as a rule, if they were 1 km or more from industrial chimneys, with few domestic chimneys within 100 m. For reasons that will appear, the map for chlorides includes results from some 11 gauges that do not comply with these conditions, and the amount of ash collected in the 11 gauges is used as a rough index of the contribution from chimneys to the chlorides collected. Figs. 1 — 4 were based on the entire series of observations recorded in the 26 reports of the " Investigation of Atmospheric Pollution", but where observations continued for more than 5 years the latest published 5-year average was used. To make the maps as comprehensive as possible, results were included from deposit gauges started within the last five years ; the shortest period for which an average was plotted was 6 months.

Figs. 1 — 4 may be compared with a map prepared from similar data by Dr. C. E. P. Brooks (1947). This map refers to the " total solids " deposited in country districts in Great Britain (when the material from a deposit gauge has been analysed, the weights of undissolved and dissolved matter are added together and recorded as " total solids "). As a rule, in country districts " total solids " exceeds the sum of undissolved ash, combustible matter, sulphates and chlorides by 40 to 65 per cent. owing to the presence in solution of other substances besides sulphates and chlorides.

Before estimating (from Figs. 1 — 4) the average rate of deposit over the country it was necessary to exclude the north-western half of Scotland, the western half of Wales, Cornwall and half Devon because of lack of observations, but relatively little pollution from fuel is likely to be deposited there. Even so, the maps contain large areas without observations, where notional isopleths have been drawn in broken lines. The average rates of deposit over the whole area to the east of the thick line have been evaluated from the maps, and are shown in the last row of Table I. Chlorides deposited in summer and winter were treated separately.

Atmospheric pollution in Great Britain in relation to the burning of coal

It is impossible on maps of the scale of Figs. 1 — 4 to give a representation of pollution deposited in towns, but in the first five rows of Table II estimates are given of the average rates at which pollution is deposited in two classes of County Boroughs and three industrial regions. Simple averages were taken, as a rule, for all sites in each city or area, without plotting on maps ; their contribution to the total pollution deposited on Great Britain is not large.

Table II contains the estimates, from the data of Table I, of the total deposited matter on the whole area of 65,900 mi². It is immediately evident that, although pollution from fuel must be produced mainly in the towns, far more pollution is deposited in country areas than in towns and industrial areas. The last row of

TABLE I. AVERAGE RATE OF DEPOSIT OF POLLUTION IN GREAT BRITAIN

	Pop. (million)	Area (mi^2)	No. of sites	Ash g/(m^2 mth)	Carb. g/(m^2 mth)	SO_2 g/(m^2 mth)	Chlorides Summer g/(m^2 mth)	Chlorides Winter g/(m^2 mth)
17 cities of population over 200,000 (including groups round Manchester, Newcastle and Sheffield)	16·5	1442	79	2·97	1·44	0·62	0·34	0·53
Other C.B.'s and B.'s in S. Lancashire	2·2	382	27	2·56	1·78	0·70	0·52	0·92
in Yorks., W. Riding	0·9	250	34	2·95	1·20	0·69	0·44	0·73
Black Country	0·7	76	15	3·01	1·63	0·58	0·34	0·52
42 other C.B.'s	3·5	414	7	1·47	0·87	0·41	0·32	0·69
Rest of Great Britain (except ½ Scotland, ½ Wales, ½ Devon, and Cornwall)	22·2	63336	40	0·52	0·37	0·33	0·29	0·43

Abbreviations : C.B., County Borough ; B., Borough ; SO_2, sulphates and sulphites in solution, estimated as sulphur dioxide ; Carb., combustible undissolved matter, including tar ; ash, weight of insoluble matter after ignition at 800°C.

TABLE II. DEPOSITED MATTER ON GREAT BRITAIN

	Pop. (million)	Area (mi^2)	Ash (10^6 tons/year)	Carb. (10^6 tons/year)	SO_2 (10^6 tons/year)	Chlorides Summer (10^6 tons/½ year)	Chlorides Winter (10^6 tons/½ year)
County Boroughs and industrial areas	23·8	2,564	0·21	0·11	0·05	0·015	0·025
Rest of Great Britain (except ½ Scotland, ½ Wales, ½ Devon, and Cornwall)	22·2	63,336	1·02	0·73	0·65	0·285	0·445
Total	46	65,900	1·23	0·84	0·70	0·30	0·47
Total emission from coal utilization (million tons per year)			0·5	2·3	5·0	0·5	

Table II contains the estimates of total pollution resulting from coal utilization to be found in Appendix VI of the 26th Report. Included also is an estimate of the emission of chlorides, based on the rough generalization that the average chlorine content of coal is about one fifth of the average sulphur content, little sulphur or chlorine being retained in the flues or ash pit after combustion.

The last two rows of Table II show plainly that further investigation is needed. Not only are there differences between corresponding items in the last two rows, but the differences are not all in the same sense. Thus, if we compare the weight deposited with the weight emitted (according to the table) the ratios are : Ash 2·5, Carbonaceous matter 0·37, Sulphur dioxide 0·14, Chlorides 1·5. This fact shows that there can be no general comprehensive explanation for the discrepancies in Table II, and in Part 2, the four items are considered separately.

2. Types of atmospheric pollution

(a) *Ash from coal, and in deposit gauges*

In Table II, the weight of ash collected in deposit gauges is given as about 2·5 times the weight resulting from coal utilization. I think that, when more data enable the two estimates to be revised, they will be in much better agreement. In other words, I do not think any important fundamental consideration is involved.

First, the estimate of the weight of ash emitted may be low. It is based on information obtained a few years before 1939, when the annual coal consumption was 176 million tons, and it amounts to only 0·34 per cent. of the coal utilized. Much coal is being burnt which contains 10 or 15 per cent. of mineral matter, and even the best coals contain from 1 to 2 per cent of mineral matter, of which perhaps 0·5 per cent is distributed in a finely divided state within the coal substance. It is true that when high-ash coal is burnt the major part of the ash reaches the ash pit ; but the finely divided ash is likely to be liberated mainly in the form of small particles less than 10μ in size, and these are more likely to escape with the flue gases than to be attached to particles heavy enough to fall into the ash pit. Flue-gas velocities of 30-40 ft/sec are common in industrial installations, and these are sufficient to lift ash particles of over 400μ (0·4 mm) diameter.

It should also be observed that the estimate of deposited ash in Table II will exceed the estimated emission if particles are blown from the ground into deposit gauges more frequently than from deposit gauges to the ground. When grass-land was ploughed near a deposit gauge at Godalming, and intensively cultivated, there was an increase of 25g/(100m^2 mth) in the ash collected. This may be taken as an extreme case since the gauge was in a windy position and the soil was light, sandy, and often dry. It is doubtful whether, over the country as a whole, more than 5g/(100m^2 mth) can be attributed to wind-blown mineral matter ; this would reduce the estimate of ash deposited on Britain by 0·1 million tons per annum.

On the whole it seems likely that, with adequate observations, the annual emission and deposition of ash in Great Britain would be found to be approximately equal ; and that the true figure is at least 1·0 million tons.

(b) *Smoke from coal, and carbonaceous matter in deposit gauges*

(i) *Weight of smoke*

The weight of smoke emitted from a chimney is determined from the loss in weight when the particulate matter, collected from samples of the gases passing up the chimney, is ignited at 875°C in a crucible. The weight of carbonaceous matter in a deposit is estimated from the loss in weight when the undissolved matter from the deposit gauge is similarly ignited.

It certainly seems probable that the carbonaceous undissolved matter in deposit gauges is caused by the smoke made during coal utilization ; but, if so, a reason must be found for the fact that, by Table II, only 0·37 of the material emitted is collected by deposit gauges.

In the towns, some of the carbonaceous matter collected by the deposit gauges consists of relatively large cokey particles, of diameter about 50μ, which are liable to be emitted from industrial chimneys ; and in all districts there is a risk that

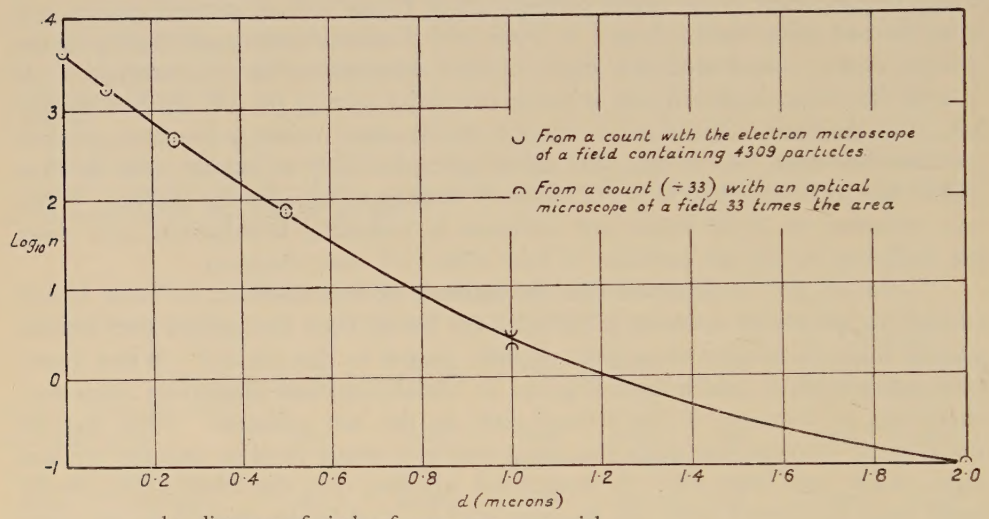
vegetable matter or insects may be included with the carbonaceous matter. Both these considerations tend to widen the difference in Table III and there is no very obvious way in which the difference could be narrowed.

The main reasons for the difference in Table II must be either

(a) that the deposit gauge does not collect a fair sample of the smoke deposited on the ground, or

(b) that some of the smoke produced in Great Britain is blown away to sea before it can be deposited.

These reasons can better be discussed when the average size of smoke particles and their rate of fall in still air are known.



d : diameter of circle of same area as particle.
n : number of particles larger than d on a definite area of surface.

Figure 5. Particle size distribution of atmospheric smoke — N.P.L. 7-9 December 1943.

(ii) *Size of smoke particles*

In 1943 samples of smoke in the open air of Teddington were collected on a thin film of collodion, by using a thermal precipitator. The samples were examined in the electron microscope with the help of Metallurgy Division, National Physical Laboratory. Plates I and II show specimen samples ; like all others examined, these consist chiefly of approximately round particles, with a few chains composed of round units. In an optical microscope the latter could easily be taken for single particles ; Fig. 5 is a representation of the size distribution, and Table III summarizes the results.

TABLE III. Size distribution of smoke particles at Teddington, 7-9 Dec. 1943

1. Particles less than 0·075μ in diameter constitute half the total number.
2. Particles less than 0·23μ in diameter occupy half the length if all particles placed in line.
3. Particles less than 0·35μ in diameter cover half the total area of deposition.
4. Particles less than 0·51μ in diameter occupy half the total volume.

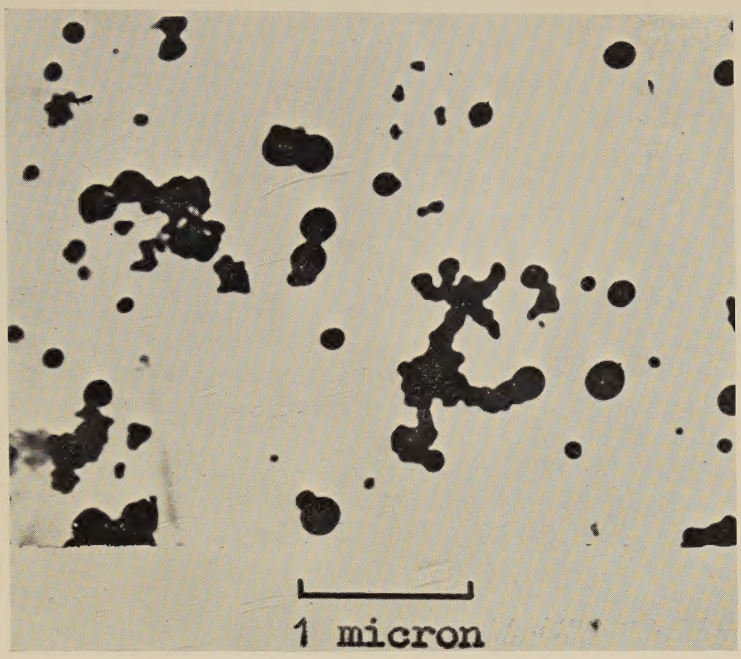


Plate I

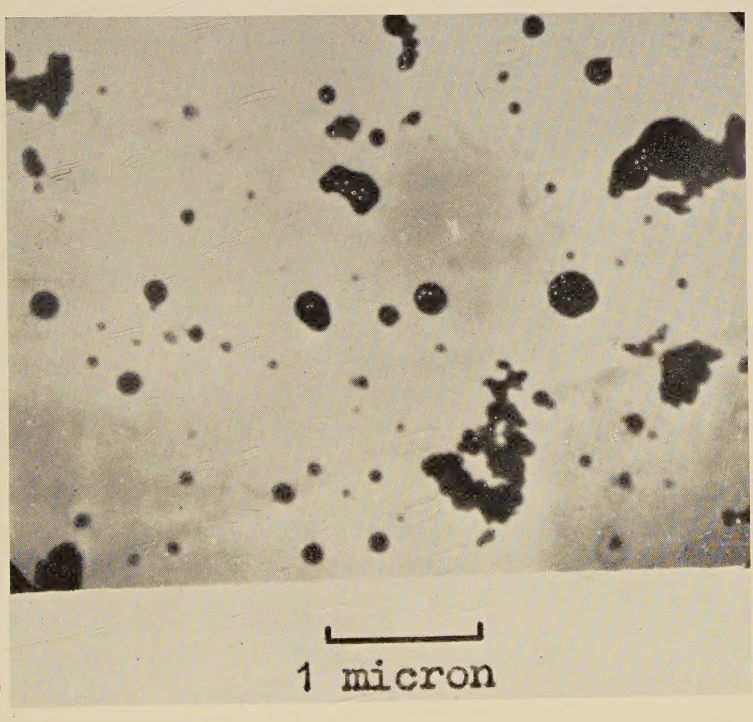


Plate II

Plates I and II : Electron micrographs of smoke ; Teddington, December 1943.

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In the table, row 3 was determined by direct observation, and the other rows were calculated on the assumption that the particles were caught directionally at random on the collodion ; *i.e.*, that if each particle were rotated through any angle, the area-distribution would be the same as in Fig. 5. The thermal precipitator was used to collect two samples simultaneously, the second of which was examined with an optical microscope over the greater part of its area ; and by uniting the results with those of the electron microscope, it was shown that only about 200 particles in a million were larger than 1μ and only about 10 particles in a million were larger than 2μ in diameter.

It is by no means obvious how particles of the sizes in Table III are removed from the air, but no one would suggest that the process is simply one of settlement under gravity : for example, a spherical particle of diameter $0{\cdot}1\mu$ and density 2 would fall in still air at $2{\cdot}5 \times 10^{-5}$ cm/sec and would take 46 days to fall to the ground from a height of 10m. The quantities removed from the air, and the time taken in removing them, are discussed below, in section 2 (d).

The bearing of this conclusion on the present discussion is clear :

(a) there is no reason to suppose that a deposit gauge collects a representative sample of the smoke particles which, as we know, are deposited on vertical walls, ceilings, grass and foliage as well as horizontal surfaces, and

(b) there is every reason to expect that some of the smoke produced in Great Britain is blown out to sea.

Because of their small surface area, deposit gauges probably collect less than their share of deposited smoke, but they may collect other combustible material which is not smoke. It is a matter of conjecture whether the weight of smoke deposited annually in Britain is more or less than the 0·84 million tons given in Table II, but if it is 0·8 million tons, then 1·5 million tons must be blown to sea. In section 2 (d) the consequences will be examined of assuming that 1·5 million tons of smoke are blown to sea each year.

(iii) *Concentration of smoke in surface air*

For a satisfactory discussion of the ways in which smoke escapes from the air of Britain it would be necessary to know the total weight of smoke in the air of Britain, or its average over several years. This is not known, and there have been extremely few measurements of smoke in the free atmosphere (Lettau 1937). Recently, however, there has been a considerable increase in the number of country places where regular measurements are made of the concentration of smoke in surface air.

Figs. 6 and 7 show the general average distribution of smoke in surface air in summer and winter, as measured by drawing samples of air through white filter paper, and comparing the shade of the smoke stain with a calibrated scale of shades. (Many of the observing stations have been in operation for one year only, and at a later date the maps will require revision — a suitable period for averages of this type would be 2 - 5 years.) There are several large areas with no observations, but after taking note of the distribution of population and industry, an estimate can be made of the average concentration. In mg/(1000m^3) it is : summer, 29 ; winter, 75 ; year, 52. The maps do not include observations in towns and, if

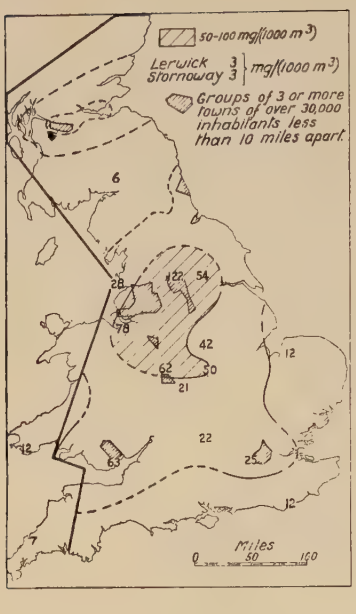
50-100 mg/(1000 m³)
Lerwick 3
Stornoway 3
mg/(1000 m³)
Groups of 3 or more towns of over 30,000 inhabitants less than 10 miles apart
Miles
0 50 100

Figure 6. Summer mean.

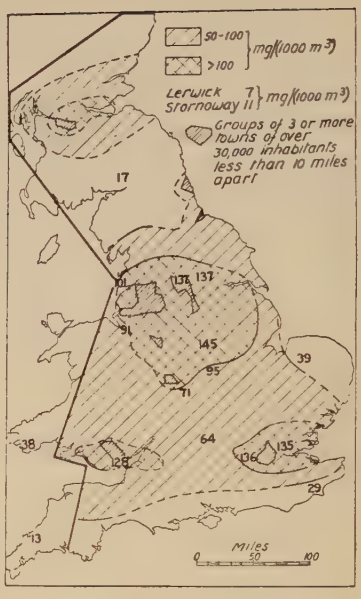

Figure 7. Winter mean.

Figures 6 — 7. Smoke in surface country air, mg/(1000m³).

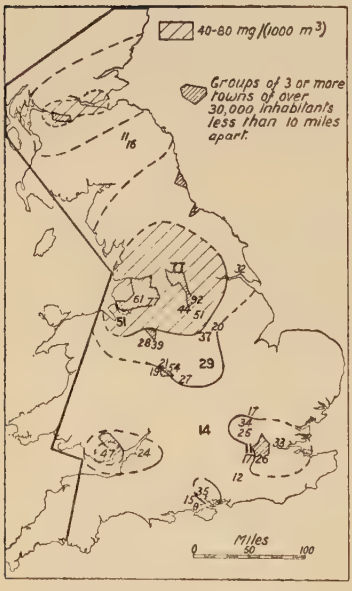

Figure 8. Summer mean.

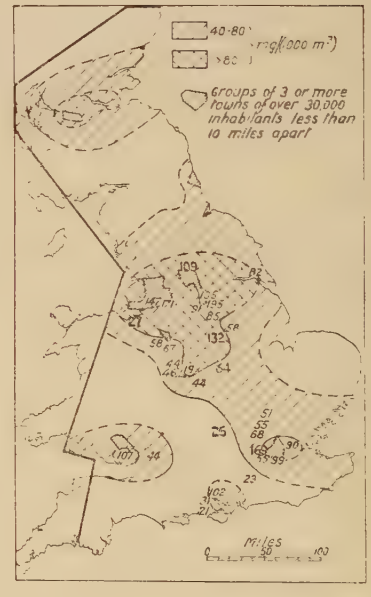

Figure 9. Winter mean.

Figures 8 — 9. Sulphur dioxide in surface country air, mg/(1000m³).
Plain figures: volumetric method. Sloping figures: lead peroxide method.

allowance is made for the high concentrations of smoke in the relatively small areas of towns, the yearly average concentration is 57 mg/(1000m^3).

If at different heights above the ground the concentration of smoke obeyed a simple law it would be possible to calculate the yearly average of the total weight of smoke over Britain. Unfortunately there is no such law for, in turbulent weather in the open country, smoke may be observable right up to the tropopause ; but in the absence of turbulent mixing, or near towns, the greater part of the smoke is likely to be concentrated near the ground. There will however be some factor $\bar{h}$, of the dimensions of a length, such that the yearly average of the total weight of smoke over Britain is $c_1\bar{h}A$, where c_1 is the average concentration of smoke already determined, and A is the area of Britain. Clearly $\bar{h}$ will depend on (1) the frequency of occurrence of various weather conditions, (2) the disposition of towns and other sources of smoke, and (3) to a relatively small degree, on the rate of deposition of smoke on the ground.

The observations of Lettau (1937) indicated that the total mass of smoke in the air might be calculated from the concentration at the surface by assuming a uniform density of smoke to heights ranging from 0·2 to 2·0 km, and no smoke above these heights ; *i.e.*, $\bar{h}$ was from 0·2 to 2·0 km on these occasions.

The total weight of smoke over Britain, $c_1\bar{h}A$, will be connected with the rate l_1 at which it is blown to sea, by a relation $c_1\bar{h}A = l_1\bar{T}$, where $\bar{T}$ is a weighted average of the time taken by air to reach the coast after being charged with smoke. A rough estimate of $\bar{T}$ may be made as follows. The area of Britain under consideration, 65,900 mi^2, is equivalent to a circle of radius 145 miles. From records (Bilham 1938) of the frequency of winds of different velocity at Kew, the average distance travelled by surface air in one hour is 7·99 miles. At Birmingham, 643 ft above sea level, it is 10·09 miles. The inland average must therefore be about 9 miles. Without any attempt at making a properly weighted determination of $\bar{T}$, a reasonable value would appear to be $\bar{T} = 145/9 = 16$ hours.

The discussion of the balance of smoke in the atmosphere will be resumed after the observations of sulphur dioxide have been treated in the same way as those of smoke. It will be found helpful to make the fairly plausible assumption that $\bar{h}$ and $\bar{T}$ are the same for sulphur dioxide in the air over Britain as for smoke.

(c) *Concentration of sulphur dioxide in surface air*

In Table II, it was shown that seven times as much sulphur dioxide is emitted in Britain as is indicated by deposit gauges as being deposited. As with smoke, it seems reasonable to try the supposition that some sulphur dioxide is blown to sea, bearing in mind also that more may be deposited than is indicated by deposit gauges.

Figs. 8 and 9 are maps of the average concentration of sulphur dioxide near the ground in country districts, in summer and winter. They are based partly on direct determinations of the concentration of sulphur dioxide and partly on the rate at which it is absorbed from the open air by a surface of lead peroxide, prepared and exposed in a standard manner.

The correspondence between the two methods is not perfect, but the readings by the lead-peroxide method (milligrammes of sulphur trioxide per day collected by 100cm² of lead-peroxide surface) were converted to concentrations in mg/(1000m³) by multiplying by a factor of 71·5, found by a comparison of observations at country stations. As in the case of smoke there are several large areas with no observations. Excluding Scotland entirely, the estimated average concentrations in the area east of the black line are : summer, 24 ; winter, 52 ; year, 39, mg/(1000m³). Extended to include Southern Scotland in proportion to smoke, the yearly average is 37. If allowance is made for the sulphur dioxide in towns, of which many observations have been made, the average surface concentration for the whole country is 41 mg/(1000m³).

(d) *Balance of smoke and sulphur dioxide in the air*

By introducing the assumption, referred to in an earlier paragraph, that 1·5 million tons of smoke are blown to sea each year, it is now possible to evaluate other properties of smoke and sulphur dioxide in the atmosphere. Bold type is used for symbols representing quantities that have been determined (or assumed), and the suffixes 1 and 2 refer to smoke and sulphur dioxide. All quantities have been expressed in cgs units.

	Smoke	Sulphur dioxide
Rate of emission	$m_1 = 0{\cdot}77 \times 10^5$ g/sec	$m_2 = 1{\cdot}6 \times 10^5$ g/sec
Blown to sea	l_1 ($= 0{\cdot}48 \times 10^5$ g/sec)	l_2
Average concentration in surface air	$c_1 = 0{\cdot}57 \times 10^{-10}$ g/cm³	$c_2 = 0{\cdot}41 \times 10^{-10}$ g/cm³
Average life over land before being deposited	t_1 sec	t_2 sec
Area of Britain considered	$A = 1{\cdot}708 \times 10^{15}$ cm²	$(= A_1 = A_2)$
Time for pollution to reach coast	$\bar{T} = 5{\cdot}76 \times 10^4$ sec	$(= \bar{T}_1 = \bar{T}_2)$
Height factor	$\bar{h}$ cm	$(= \bar{h}_1 = \bar{h}_2)$

The above quantities are connected by the following relations :

$l_1\bar{T} = c_1A\bar{h}$ $\quad l_2\bar{T} = c_2A\bar{h}$ $\quad$ (whence $l_1/l_2 = c_1/c_2$)

$\bar{T} = t_1\log(m_1/l_1) = t_2\log(m_2/l_2)$ (assuming the deposition on land occurs according to an exponential law).

It will be seen that there are four and only four independent equations from which four unknowns must be determined. Their values are :

l_2	$= 0{\cdot}345 \times 10^5$ g/sec	$= 1{\cdot}1$ million tons/yr	(0·7 million tons/yr)
$\bar{h}$	$= 2{\cdot}8 \times 10^4$ cm	$= 280$ m	(190 m)
t_1	$= 12{\cdot}2 \times 10^4$ sec	$= 34$ hr	(18 hr)
t_2	$= 3{\cdot}76 \times 10^4$ sec	$= 10\frac{1}{2}$ hr	($8\frac{1}{4}$ hr)

The values in brackets are reached by assuming l_1, the weight of smoke blown to sea, is 1·0 million tons per annum instead of 1·5 million tons per annum. The results can be summarized :

Of the 2·3 million tons of smoke emitted per year it is assumed that 1·5 million tons are blown to sea ; the remaining 0·8 million tons are deposited on land, and if this occurs according to an exponential law, the average life of a smoke particle is 34 hours.

Of the 5·0 million tons of sulphur dioxide emitted each year, it follows that 1·1 million tons are blown to sea ; the remaining 3·9 million tons are deposited on land, and if this occurs according to an exponential law, the average life in the air of a molecule of sulphur dioxide is $10\frac{1}{2}$ hr.

It also follows that the total weight (averaged over a long period) of smoke or sulphur dioxide over Britain can be calculated, from their average concentration in surface air, by imagining this concentration to persist to a height of 280 m, with nothing above.

The quantities in the above summary depend upon the assumption as to the amount of smoke blown to sea ; if this could be measured directly, or if any one of the other four unknowns, l_2, t_1, t_2, or h, could be determined, a much more satisfactory solution could be found. Whatever the true values may be, however, we can be confident that the average life of a smoke particle is longer than that of a sulphur-dioxide molecule, and that a greater proportion of smoke than sulphur dioxide is blown to sea. These two generalizations follow from the observed fact that, although more sulphur dioxide than smoke is produced, the concentration of smoke is greater than of sulphur dioxide.

In the Leicester Report (1945) even cruder estimates were given which were based on observations in the Midlands only, there being no allowance for pollution entering and leaving the area, and $\bar{h}$ being taken as 700 m. The average life of a sulphur dioxide molecule was given as 3 days and of a smoke particle as 6 days.

Further than this it would not be wise to go, though some important features of climate have been touched on. Pollution, even if it takes a form that cannot be deposited by gravity, apparently has a relatively short life in the atmosphere. Its method of removal from the atmosphere is far from clear, but the following factors are likely to be important :

(1) the rate of free fall
(2) the atmospheric diffusivity at all heights, and especially within a few metres of the surface since this will influence the frequency of collision between the particles of atmospheric pollution and the surface
(3) the rate of molecular or Brownian diffusion of the pollution very close to the surface
(4) the nature of the surface and of the pollution, affecting the probability that on collision the pollution will adhere to the surface
(5) the specific area available for deposition in unit area of the surface, and
(6) the direct effect of rain and other meteors, and their influence on (4) and (5).

If more definite information could be obtained about these factors and about the general question of the influence of climate on pollution, there would be a better chance of dealing effectively with the still more intricate influence of weather on pollution. In particular, there is great need for simple, easily measurable

parameters for describing atmospheric diffusivity in so far as it affects the dilution and deposition of pollution.

(e) *Chlorides*

There still remains in Table II one item that has not been discussed. The estimates of chlorides deposited and emitted from chimneys are in fair agreement at about half a million tons per annum, but the agreement is probably a spurious one. The distribution of chlorides deposited in country districts is distinctly different from that of other forms of atmospheric pollution (Fig. 4 compared with Figs. 1, 2 and 3).

Fig. 4 may also be compared with measurements of chlorides in rain water and drainage water. Miller (1906) and Russell and Richards (1920) showed that at Rothamsted the long-period averages of chlorides in rain water, and drainage water from bare soil, were closely equal at about 15 lb acre^{-1} yr^{-1}, *i.e.* 14 g/(100m^2 mth). Hendrick and Welsh (1938) found about 56 lb acre^{-1} yr^{-1}, *i.e.* 15 g/(100m^2 mth) of chlorides in drainage water, about three miles from the sea near Aberdeen, from unfertilized land on which was grown a rotation of crops. These results, taken all together, strongly suggest that the main source of the chlorides deposited in country districts is not the fuel burnt in towns and industrial regions, but the sea ; the deposits seem to be heaviest near the coast, and not particularly heavy near industrial centres.

In support of this, there seems to be a tendency for exceptionally heavy deposits of chlorides — as much as two or three times the average — to occur in all districts during months of stormy weather. Correlation coefficients have been determined for certain groups of deposit gauges in winter, between deposits of chlorides, the number of days per month when the maximum hourly wind run at an exposed station exceeded 24 mi, and the number of rain days per month (meteorological data were taken from the *Monthly Weather Report*). For series of 45 to 80 winter months the correlation between chlorides and high winds was + 0·68 at Southport ; + 0·66 for country districts near Burnley, Keighley, and Manchester ; + 0·55 for Bournville Village (Warwicks), Dore (Derbyshire), Garston (Herts), Godalming (Surrey), Loggerheads (Staffs), and Marple (Cheshire) ; and + 0·60 for country districts near Edinburgh, Newcastle, and Kingston-upon-Hull (in the last case high winds from the N., NE., E., and SE. only were considered). The only significant correlation between chlorides and rain was at Southport (+ 0·31) and here the partial correlation between chlorides and high winds, rain being kept constant, was + 0·63.

The combined evidence of the map and the correlation coefficients suggests very strongly that some at least of the chloride substance collected in deposit gauges originates from the sea, and especially from the drops of sea water that are torn from the crests of waves during gales.

Before leaving the subject of chlorides from the sea, it is of interest to consider the deposition of other sea salts which might be important in agriculture. Sea water contains (in g/kg) : chlorides 19·3 ; sodium 10·7 ; sulphates 2·7 ; magnesium 1·2 ; calcium 0·42 ; potassium 0·38 ; others 0·3. Taking the evidence of the correlation coefficients and of Fig. 4, chlorides from the sea are apparently deposited

in non-industrial districts at an average rate of about 0·1 g/m² mth, equivalent to an annual deposit of about 3 tons/mi² or 11 lb/acre. As the maps indicate, these figures may be doubled in coastal regions and halved in the Midlands.

If the other constituents are deposited in proportion to the chlorides, there will be an average annual deposit of 20 lb/acre of sea salts (equivalent to about one tenth of the dissolved solids in rural deposit gauges). The corresponding deposits of the separate constituents (in lb/acre) are : sodium, 6 ; sulphates, 1·5 ; magnesium, 0·7 ; calcium 0·2 and potassium 0·2. The amounts of sulphates and calcium are less than 5 per cent. of the deposits observed in rural deposit gauges.

Further investigations of chlorides in the atmosphere are perhaps even more desirable than of other forms of atmospheric pollution. Since plants do not assimilate chlorides, it would be highly interesting to test whether the chlorides per acre in rain and in drainage water from bare soil are exceeded by the chlorides in drainage water from land carrying vegetation. Near the sea this will almost certainly be the case, but it is not known how far inland the effect will persist. Such an investigation might provide direct evidence that vegetation can help to rid the air of pollution.

A second problem is the behaviour of chlorides (and of sulphur dioxide) emitted to the atmosphere from the combustion of coal. Any estimate of the total deposits of chlorides from coal, for insertion in Table II, would evidently be considerably less than the quantity emitted from chimneys, implying that some of the chloride from coal is either blown to sea or is not adequately sampled by deposit gauges ; in the latter case, it cannot all be removed by rain, since deposit gauges sample rain perfectly. It has been suggested that chlorides from coal are emitted to the atmosphere as hydrogen chloride, either in the gaseous state, or dissolved in water droplets. Whether a significant proportion of the hydrogen chloride is gaseous, and whether individual molecules would form effective condensation nuclei, we do not know at present.

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Evaporation over the British Isles

By H. L. PENMAN
Rothamsted Experimental Station

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SUMMARY

Theoretical values of average annual evaporation from the British Isles are calculated from long-term averages of air temperature, duration of sunshine, vapour pressure and wind speed for about 100 stations. Direct estimates of the same quantity are obtained from long-term averages of annual rainfall and annual run-off from about 40 catchment areas. The two kinds of estimate agree and are plotted on a map to show the geographical variation of evaporation. This shows an increase from 14 in. per annum in Scotland to 20 in. along the south coast.

1. INTRODUCTION

Natural evaporation is an important phenomenon in several branches of meteorology. In meteorological physics it is intimately involved in the heat balance of the land, the ocean and the atmosphere ; in applied meteorology it can be the dominant factor in successful agriculture and in practical hydrology. Direct measurement of evaporation from natural surfaces is almost impossible, but there are circumstances in which indirect estimates can be made. If sufficient values are obtained for a range of weather conditions it may be possible to obtain a statistical correlation between evaporation and such known weather parameters as are thought to be relevant. At best this type of approach provides a useful relation but rarely a reason, and extrapolation to other times and other places may be unreliable.

The possibility of a successful synthesis depends upon the possession of a body of fundamental knowledge sufficiently broad and sufficiently accurate to permit formulation of a theory, to establish reasons and thence to derive relations that can be matched with experience. This state of affairs has now been reached in evaporation studies, for during the past two decades the physics of the process has become sufficiently clear to be of practical use, and though future research may modify details the broad picture is unlikely to change. Reviews of some or all aspects of this fundamental work are available in Brunt (1939), Sutton (1950), Priestley (1949), Pasquill (1943, 1949) and Penman (1948a).

The present survey was foreshadowed in an earlier account of theoretical and experimental work at Rothamsted (Penman 1948b) in which it was shown that combination of the two classical approaches to evaporation studies — turbulent transport and energy balance — could make use of existing weather records to provide retrospective estimates of natural evaporation. Since then Pasquill (1949) has shown that some of the assumptions made may not be reliable under all weather conditions, particularly for short periods of a day or less, but over a season or a year the error is no more than that which might arise from many other sources of uncertainty. If Pasquill's criticism is accepted as valid, the estimates of yearly

evaporation given in this account may be about 5 per cent. too high. Since 1948 the treatment has been applied to particular problems with encouraging success, *e.g.* to the control of irrigation experiments (Penman 1949b), and to a detailed study of the water balance of a catchment area (Penman 1950), among others. In all these the direct measures of evaporation that have been sought as checks have proved to be less precise than the theoretical estimates. The present account extends the testing to the British Isles as a whole, using data for rainfall and run-off for catchment areas to derive values of natural evaporation.

2. Estimation of transpiration

The complete process involves three stages.

(1) An estimate is made of the hypothetical evaporation that would take place from an extended sheet of open water exposed to the weather conditions found over the site. This is E_o.

(2) A seasonal correction factor is applied to convert to the potential transpiration that would take place from the area if it were covered by green vegetation never short of water. This is E_T, and is equal to $E_o \times f$.

(3) Although it will not be used here, a correction can be made for the depth of rooting of the vegetation which controls the availability of water during rainfall-deficient periods in summer (Penman 1949a). If the corrected value is E, then $E \leqslant E_T$, but over most of the British Isles in all years $E \simeq E_T$, and in many years the equality is true for the whole of the area. In dry summers in South and South-East England E will be less than E_T, but for a rapid survey it is convenient to assume $E \equiv E_T$, knowing that over a long period of years the error will not be very great. (For the Suffolk Stour area the mean values 1933-1948 are $\bar{E}_T = 21{\cdot}5$ in.; $\bar{E} = 20{\cdot}1$ in.)

As the physical argument has already been set out in full (*e.g.* Penman 1948b or 1949b) it will be sufficient here to indicate the principles and the working equations. The rate of evaporation is limited partly by the available energy supply, and partly by the ability of the air to take up more vapour. Either conception may be used to give an estimate of E_o, but each involves an unknown surface temperature. Combining the estimates to eliminate this unknown gives

$$E_o = (\Delta H + 0{\cdot}27\, E_a)/(\Delta + 0{\cdot}27) \text{ mm/day},$$

where the symbols have the following meanings :—

Δ = slope of vapour pressure curve for water at mean air temperature T_a (mm mercury/°F)

$H = R_A(1-r)(0{\cdot}18 + 0{\cdot}55n/N) - \sigma\, T_a^4(0{\cdot}56 - 0{\cdot}092\sqrt{e_d})\,(0{\cdot}10 + 0{\cdot}90\, n/N)$

$0{\cdot}27$ is the constant of the standard hygrometer equation (mm/°F)

$E_a = 0{\cdot}35(e_a - e_d)(1 + u_2 \times 10^{-2})$ mm/day

The new symbols are :—

R_A = theoretically calculable amount of radiation that would reach the earth in the absence of an atmosphere, converted to an evaporation equivalent by putting 59 cal/cm^2 = 1 mm evaporation.

r = reflection coefficient, to be taken as 0·05. For standard evaporation tanks with light walls and clean water it may be very much greater.

n/N = actual/possible hours of sunshine. In the first term in H it is a factor limiting incoming short-wave radiation ; in the second it is a transform of a cloudiness factor limiting outward long-wave radiation.

σT_a^4 = theoretical black-body radiation at mean air temperature T_a ; this too is in evaporation units like R_A.

e_d = saturation vapour pressure at dewpoint (mm Hg).

e_a = saturation vapour pressure at mean air temperature ; hence $(e_a - e_d)$ is the mean saturation deficit.

u_2 = average wind speed in miles/day at 2 m above the ground.

It will be noted that apart from a few standard quantities obtainable from tables, the only weather data required are mean duration of bright sunshine (for n/N), mean air temperature (chiefly for e_a and σT_a^4), mean vapour pressure, and mean wind speed. All can be obtained from the *Monthly Weather Report* published by the Meteorological Office.

To convert E_o to E_T, values of f must be known. Most of the calculations have been on an annual basis, using $f = 0{\cdot}75$. For a few sites where monthly values have been estimated the following values of f have been used :—

Period	f
Nov.-Feb. (inc.)	0·6
Mar., Apr., Sept., Oct.	0·7
May-Aug. (inc.)	0·8

These are empirical values and will be used as such, but from considerations of leaf structure and changing length of daylight it has been possible to justify the order of magnitude on theoretical grounds (Penman and Schofield 1950).

3. Sources of weather data

All values of air temperature and duration of sunshine have been taken from M.O. 407 (1936) and 408 (1936) respectively. Values of vapour pressure and wind speed have been kindly supplied by the Climatology Branch of the Meteorological Office in two forms that automatically separate the evaporation estimates into two groups of different reliability. Group one, the more reliable, is based on tables of mean monthly values of vapour pressure and wind speed for particular stations ; Table I contains the values of E_o for 25 stations in this group. The less reliable second group of estimates has used values of mean annual vapour pressure and mean annual wind speed read from climatological maps of these elements at the positions of stations for which temperature and sunshine data were available. Where necessary, vapour pressures were corrected for altitude to give the value at station level.

As it was not to be expected that the sum of twelve monthly means would be exactly equal to the annual mean, the annual value was calculated for 15 stations, spread as fairly as possible over the British Isles, for which monthly values had been calculated. The general ratio of the sum of the 12 monthly means to the annual mean was 1·14, individual values ranging from 1·09 to 1·21. The con-

sistency was such that it seemed reasonable to multiply all estimates of E_o obtained from mean annual data by 1·14 to convert to the value that would have been obtained had it been possible to work from mean monthly data. Experience — limited almost entirely to Rothamsted data — indicates that no significant change in estimates is produced by working with periods shorter than a month.

It is to be noted that the periods over which the weather parameters have been averaged are not the same for all four weather elements. More extreme differences in period will be found in the averages of difference between rainfall and run-off.

4. Seasonal change in E_o

Although the main object of this paper is to estimate actual evaporation from natural land surfaces, the hypothetical open water evaporation is of some interest as a climatic element, and might be of direct use in estimating losses from reservoirs and lakes. Values for 25 stations appear in Table I.

TABLE I. Estimated monthly evaporation from open water (inches)

Site	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Stornoway ..	0·3	0·6	1·1	2·2	3·2	3·7	3·2	2·4	1·7	0·7	0·1	0·2	19·4
Aberdeen ..	0 2	0·6	1·3	2·3	3·2	3·6	3·5	2·9	1·7	0·9	0·2	0·1	20.5
Eskdalemuir ..	—0·0	0·5	1·1	2·0	2·7	3·7	3·2	2·5	1·4	0·6	—0·0	—0·1	17·6
Southport ..	0·2	0·7	1·5	2·7	3·9	4·3	4·2	3·6	2·2	1·1	0·1	0·1	24·6
Liverpool ..	0·5	1·0	1·8	3·0	4·0	4·6	4·4	3·6	2·4	1·4	0·5	0·4	27·6
Holyhead ..	0·4	0·8	1·8	2·7	3·5	4·2	4·0	3·4	2·3	1·4	0·7	0 4	25·6
Manchester ..	0·6	0·9	1·4	2·6	3·9	4·2	4·0	3·0	2·0	1·1	0·2	0·2	24·1
Birmingham ..	0·3	0·7	1·7	2·6	3·7	4·2	4·5	3·7	2·4	1·1	0·4	0·1	25·4
Catterick ..	0·1	0·5	1·0	2·2	3·2	3·6	3·4	2·5	1·6	0·8	—0·1	—0·1	18·7
Spurn Head ..	0·1	0·5	1·1	2·4	3·4	4·1	4·3	3·6	2·3	1·1	0·4	0·1	23·4
Mildenhall ..	—0·1	0·5	1·4	2·4	3·8	4·3	4·3	3·5	2·0	0·7	—0·1	—0·0	22·7
Yarmouth ..	0·1	0·6	1·3	2·7	3·7	4·4	4·4	3·7	2·3	1·1	0·2	0·0	24·5
Felixstowe ..	0·3	0·8	1·7	2·9	4·1	5·0	5·1	4·3	2·8	1·6	0·4	0·2	29·2
Shoeburyness ..	0·1	0·6	1·5	2·5	3·8	4·5	4·7	3·8	2·1	1·0	0·2	—0·1	24·7
Kew	0·3	0·8	1·7	2·8	4·3	5·1	4·7	3·9	2·4	1·2	0·4	0·3	27·9
Croydon	0·3	0·8	1·8	2·8	4·0	4·9	5·0	4·0	2·5	1·2	0·4	0·2	27·9
Lympne ..	0·1	0·6	1·6	2·7	3·9	4·5	4·7	3·8	2·4	1·2	0·3	0·0	25·8
Calshot	0·4	0·9	1·8	2·9	4·2	5·1	5·1	3·8	2·7	1·4	0·6	0·2	29·1
Porton	0·2	0·6	1·5	2·5	3·6	4·5	4·5	3·3	2·2	0·9	—0·1	—0·2	23·5
Plymouth ..	0·8	0·9	1·7	3·0	3·7	4·7	4·4	3·4	2·5	1·3	0·5	0·3	27·2
Falmouth ..	0·9	1·5	2·1	3·2	4·1	4·2	4·8	3·9	2·6	1·7	0·7	0·5	30·2
Scilly ..	0·6	1·0	1·7	2·7	3·5	4·3	4·2	3·3	2·3	1·3	0·8	0·6	26·3
St. Ann's Head ..	0·8	0·9	1·1	2·6	3·4	4·2	4·2	3·3	2·2	1·3	0·7	0·4	25·1
Valentia	0·6	1·0	1·8	2·9	3·7	4·0	3·7	3·2	2·1	1·3	0·6	0·5	25·4
Armagh ..	—0·0	0·5	1·3	2·5	3·4	3·8	3·5	2·9	1·9	0·8	0·1	—0·1	20·6

Direct checks are almost unobtainable, but through the courtesy of Mr. B. W. Bryan of the South Essex Waterworks, some evaporation figures have been supplied for the Abberton reservoir near Colchester. The data are monthly values for July, August and September from 1940 to 1947, the eight-year means being, in order, 4·34, 4·42 and 3·13 in., total 11·9 in., and these might reasonably be compared with the Shoeburyness figures from Table I. Some allowance must be made for

the thermal capacity of a large body of open water which will cause a phase lag between the time of maximum energy supply and the time of maximum evaporation, a lag that amounts to a few months for the great lakes (Folse 1929), and the oceans (Sverdrup 1945). Quite good agreement is obtained here if a phase lag of half a month is assumed, *i.e.* by taking the theoretical estimate* for July as the mean of the June and July estimates of Table I; and similarly, for August and September. Treated in this way the Shoeburyness data give estimated monthly evaporation as 4·6, 4·25 and 2·95 in., total 11·8 in.; the agreement in the individual values and the total is as good as can be expected.

Widespread correspondence has failed to find any other large open water surface for which similar direct estimates of evaporation have been made.

Some entries in Table I are outstanding. Liverpool (Bidston) has a bigger annual total than either Holyhead or Southport: the cause was found in the abnormally low vapour pressures as measured at the Bidston observatory, for which the published annual mean is 9·9 mb (M.O. 421, 1949). On the climatological map, Bidston lies on the *high* side of the 10 mb line and using this map value to calculate an annual value of E_o the result was, after correction, 24·5 in., almost the same as the entry for Southport. It would be of interest to know the extent of the area round Bidston which appears to have air drier than would be expected from conditions at neighbouring weather stations, and to know the cause of the difference. At Felixstowe, another station giving a high value of E_o, the excessive drying conditions do spread a considerable distance inland, for it has been found that the seasonal and year-to-year changes in the running of the river Stour can only be interpreted if the drying conditions are extreme over the greater part of the catchment (Penman 1950). No evidence is available to show whether the high values at Calshot and Falmouth arise from peculiar local conditions or from faulty basic theory.

The seasonal cycle is roughly sinusoidal at all stations, with the midsummer peak narrower than the midwinter trough. Plotting monthly evaporation as a percentage of annual evaporation, slight differences are found. Comparing Scilly and Kew, Scilly shows a higher winter minimum and a lower summer maximum; the Kew maximum occurs slightly earlier than that in Scilly and is more nearly in phase with the peak of solar radiation. The corresponding curves for Aberdeen and Felixstowe are almost identical with each other.

The annual value for Scilly is about as near as one can get to a value for the Atlantic. Two other theoretical estimates exist:—24·4 in. by Wüst (1922) and 26·7 in. by Frost (1946). Neither is in violent disagreement with the value of 26·3 in. for Scilly in Table I.

5. Annual evaporation over the British Isles

Values of E_o and E_T have been calculated for 102 stations represented in Fig. 1. At places like Keswick ($E_T = 16$ in.), Buxton ($E_T = 15$ in.) and Rhayader ($E_T = 17$ in.) it is possible that movement of the station by a distance very much

* Here, and later, the term "theoretical estimate" applied to either E_o or E_T means the estimate derived as set out in section 2. The basic formulae are only partly theoretical, and some empiricism must be accepted until our knowledge of the physics of evaporation is complete.

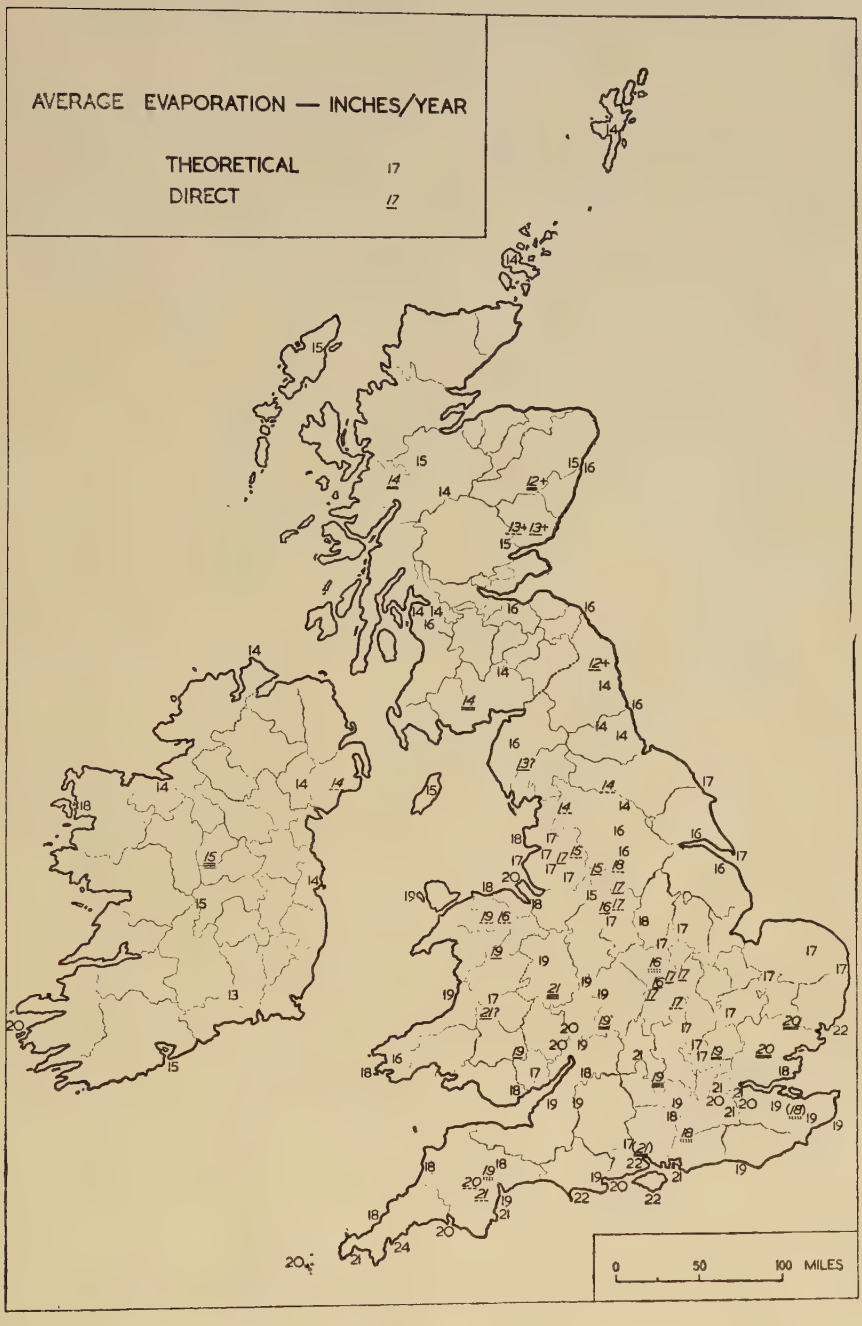
AVERAGE EVAPORATION — INCHES/YEAR
THEORETICAL 17
DIRECT 17
0 50 100 MILES

Figure 1.

smaller than that represented by the size of the figures (which are 6 mi long) would result in the return of an entirely different estimate of evaporation. Note that as in Table I, Liverpool, Felixstowe, Calshot and Falmouth are outstanding in their areas.

The physical basis of section 2 is such that the values on the map ought to be within 5 to 10 per cent. of the truth : if the "truth" can be otherwise established then the map values can be regarded as good if they are correct to within $\pm$ 1 in. per annum, and satisfactory if correct to within $\pm$ 2 in. per annum. The best available test has proved encouraging.

TABLE II. Catchment area data

Name	Area (mi^2)	Period	$\bar{R}$ (in.)	$\bar{R}-\bar{r}$ (in.)
R. Dee (Aberdeen)	528	1929-44	45·0+	12·0+
R. Inzion, Angus	9·54	1930-37	40·7+	12·6+
R. Melgam, Angus	15·8	1930-37	43·0+	12·9+
Catcleugh, Northumberland	15·4	1942-49	44·9	11·5+
Roundhill, Yorks.	4·69	1914-49	40·6	13·9
Scout Dyke, Yorks.	4·06	1930-49	40·6	18·1
Ewden Beck, Yorks.	10·15	1936-49	46·6	16·9
R. Derwent, Derby.	48·9	—	—	16·1
Burbage Brook, Derby.	3·69	1934-49	39·4	16·7
Woodford Brook, Leics.	—	—	28·4	16·0
Sywell Brook, Northants.	2·73	1933-48	24·0	16·8
Kislingbury Branch, Nene, Northants. ..	86·1	1940-45	23 6	17 1
Brampton Branch, Nene, Northants. ..	89·5	1939-45	23·8	16·3
Harpers Brook, Nene, Northants. ..	26·9	1939-45	23·8	16·6
Willow Brook, Nene, Northants. ..	36·4	1938-45	24·6	17·3
R. Stour (Suffolk)	330	1932-47	24·5	19·9
R. R. Chelmer, Ter & Blackwater, Essex	378	1932-47	23·7	19·7
R. Lea, Herts.	400	1932-47	24·9	19·4
R. Thames	3812	1917-46	29·7	19·3
Maidstone area, Kent	—	—	(28)	(18)
Compton area, Sussex	—	1921-31	39·3	17·5
R. Test, Hants.	392	—	(30)	(21)
R. Exe, Devon	—	1907-11	—	18·5
Tottiford, Devon	3·60	1914-49	44·9	20·1
Fernworthy, Devon	4·12	1929-49	73·0	20·8
R. Severn	1632	1933-48	38·1	21·0
R. Avon, Worcs.	855	1937-48	25·6	18·6
R. Vyrnwy, Montgomery	36·4	1931-38	70·1	19·1
R. Elan, Radnor	71·2	1908-48	71·7	21·1
Taf Fawr, Brecknock	16·25	1931-	—	18·9
Taf Fechan, Brecknock (not plotted) ..	13·0	various	78	19
R. Alwen, Merioneth	9·86	1922-35	55	19
R. Brenig, Merioneth	7·8	1922-35	52·8	16·3
Longdendale, Derby./Ches.	30·2	1926-48	55·4	14·5
Entwistle, Lancs.	3·32	1930-49	56·5	14·6
Rivington, Lancs.	15·2	1932-44	48·3	17·0
R. Dunsop, Yorks.	9·62	1885-13	55·4	13·8
R. Greta, Cumberland	15·8	1928-36	103·6+	12·7+
R. Dee (Galloway)	311	1930-35	67·4	13·7
R. Garry, Inverness	149	1929-44	99·5	13·9
Silent Valley, Co. Down	8·6	1934-37	70·3	13·8
R. Shannon	4020	1893-32	38·1	15·1

With the co-operation of catchment boards, water undertakings and other authorities, it has been possible to obtain records of average annual rainfall and average annual run-off for 41 catchments. The difference represents the average annual loss by evaporation, and other causes such as deep percolation. The quality of the records varies very widely, in area of catchment, in length of period, in accuracy of rain gauging and in accuracy of stream gauging. Any attempt at detailed weighting of the values would be almost impossible and only the simplest of indications has been used on the map. The values for catchment areas are underlined, with a single dashed line for an area less than 10 mi², one full line for 10 to 100 mi², two full lines for 100 to 1,000 mi², and three full lines for over 1,000 mi². Values for areas of unknown extent have a double line of dots under them. Thus Shannon, Severn and Thames are over 1,000 mi² ; the NE. Chiltern catchments are over 100 mi² ; and the Pennine catchments are just above, or just below 10 mi². (See Table 2 for details). Where the sign of an uncertainty in either rainfall or run-off is known the result is indicated on the map, *e.g.* for the Aberdeen Dee, and for Catcleugh, Northumberland ; where there is no guide to the probable sign, there is a question mark, *e.g.* for Elan in Central Wales. (These qualifying symbols are largely the result of discussions with the British Rainfall Organization and the Inland Water Survey.) Two values in brackets — near Maidstone and for the Test, Hampshire, — are not based on detailed measurements but on engineers' impressions, *e.g.* the Maidstone Water Scheme was designed on the basis of a presumed annual evaporation loss of 18 in., and the yield of water is as expected.

Assessment of the catchment data requires more information than is shown on the map, so in Table 2 are given details of the catchments as far as they are known. The order is that of the Inland Water Survey in which catchment groups are numbered clockwise round Great Britain, starting from NE. Scotland. It is thought that this table summarises nearly all the available information about average rainfall and run-off in the British Isles.

6. Accuracy

Since there are many reasons why the theoretical and direct estimates of evaporation should not be identical — they are listed below — mapping of them can only be justified if the values can be accepted as valid without major qualifications. As the two sets of data are completely independent of each other it is almost certain that if they are in agreement then both are true. As a criterion of agreement it is reasonable to expect that variation between sets should be of the same order of magnitude as the variation within sets in the same neighbourhood. By this test the agreement is extremely good — in fact, better than was expected — particularly if weighting by areas is attempted, for the values for Shannon (4,020 mi²), Thames (3,812 mi²), and Avon (855 mi²) agree within 5 per cent., and those for Severn (1,632 mi²) and the three NE. Chiltern catchments (total 1,122 mi²) agree within 10 per cent., with the direct estimates in excess of the theoretical.

The factors that might affect either of the estimates are many, too many to be discussed in detail. The following list has only occasional comments.

Estimation of E

(1) Accuracy of basic meteorological data, and in particular the reading of wind and vapour pressure from maps.
(2) Accuracy of basic formulae leading to E_o.
(3) Accuracy of conversion factor(s) in $E_T = f E_o$. In damper regions f will be slightly greater than in SE. England, depending upon how closely the mean dew point and mean minimum temperatures approach. The extent of open water in the area, and the duration of lying snow will both affect f.
(4) Accuracy of assumed identity $E \equiv E_T$. In SE. England the error here should be in the sense that $E_T - E \doteq 1$ in/annum, *i.e.* the direct estimates should be less than the theoretical by about this amount.

Estimation of R—r

(5) Accuracy of rain gauging. There are uncertainties in a few areas : to obtain a useful value for the Greta catchment ($\bar{R} = 103$ in.) for example, an accuracy of better than 1 per cent. is needed.
(6) Accuracy of stream gauging.
(7) The area of the catchment must be known, and be constant. There are doubts about some catchments (including Thames), and in some the area drained may change as well level changes.

Local factors

(8) Geological factors may result in rain falling on one catchment being discharged into another, or percolating so deeply as never to be measured. It is known that at times there is a leakage from the Lea catchment (Wooldridge and Kirkaldy 1937) into the Thames (via the Colne) and this probably accounts for the Lea ($R-r$) being greater than the theoretical estimate of E_T when in fact it might be expected to be less. Deep percolation occurs in the Thames catchment, feeding the deep water store which in the neighbourhood of Teddington is about 250 ft below O.D. (Boswell 1949). Hence, here too, $R-r$ is an overestimate of actual evaporation E, and possibly an overestimate of potential transpiration E_T. Leakage and unmeasurable deep percolation may occur elsewhere.
(9) Altitude can be important, chiefly in the effect it has on cloudiness and rainfall duration. The first affects incoming radiation ; the second affects the length of time for which the surface is wet and hence acts effectively as an open water surface, for which $f = 1$.
(10) Aspect and exposure may affect both kinds of estimate. A south-sloping valley will lose more water by evaporation than a north-sloping valley : a valley weather station may not be characteristic of more than a small area round it.
(11) Urban areas and smoke affect surface characteristics and radiation exchanges.

Biological factors

(12) The vegetative cover can be important. Areas with annual crops, deciduous trees, or annual vegetation (bracken, heather, *etc.*) will usually show less evaporation than the potential value E_T.

(13) Areas of deep-rooted vegetation will show more evaporation than those with shallow-rooted vegetation.

(14) The colour of the vegetation affects the reflected component of incoming radiation.

Time factors

(15) The weather averages leading to E_o and E_T are, in general, means for periods as follows :— Air temperature, 1906-35 ; sunshine, 1906-35 ; vapour pressure, 1921-35 ; wind, 1926-40. All are probably long enough for the purpose of this paper and the non-coincidence probably unimportant.

(16) Rainfall and run-off records are averaged over a wider range of periods : but none is less than four years. For chalk and other pervious formations where storage capacity is great the period ought to be 15 to 20 years ; over less pervious formations shorter periods can be used with safety.

(17) The actual period may be important. For several catchments the value of $R-r$ appears to have increased in the last decade. This may be a result of improved gauging or of a long-period change in storage resulting from heavier rainfall.

There is reason to suppose that none of these factors by itself will affect the evaporation estimate by more than a few per cent. Some of them involve positive corrections, some of them negative, and some can involve either positive or negative corrections. The map suggests that in general they tend to annul each other, with a possible exception in Central Wales where the sharp contrast between the Elan catchment ($R-r = 21$ in.) and Rhayader ($E_T = 17$ in.) may indicate some residual error in either or both of the estimates. Accepting this fortuitous mutual elimination of complicating factors, the map can be read without discriminating between the two kinds of estimate.

7. Discussion and applications

If lines of equal evaporation were drawn at 20 and 15 in. per annum, the former would very nearly coincide with the SE. and south coast of England and cross to SW. Ireland, with islands in the lower Thames and lower Severn valleys. The 15 in. line would, except for coastal areas, have to the north of it North England, Scotland and the east half of Ireland. An intermediate line at 17·5 in. would run from London to Liverpool. It appears that for the whole of the British Isles the annual evaporation loss is at least 14 in. : for Wales, SW. and SE. England the value is about 19 in. In trying to estimate probable yield when rainfall is known, water engineers have used an evaporation figure of 14 in. per annum for the whole of the British Isles (see *e.g.* Lapworth 1949) : over much of the country the resultant estimates of yield must be overestimates. This is of considerable importance in

any assessment of water resources available for industrial, domestic, and agricultural use ; for the last, the satisfaction of an established need for irrigation will depend on the availability of summer water supply.

As it stands, the map indicates the amount of water that would be used in an average year by plants that are never allowed to go short of water. An assessment of the requirement during the main growing period of an abnormally dry year might be even more useful, and to a very good first approximation the map figures can be read directly in this way as being the potential transpiration during six months April to September (inclusive) in a drought year (such as 1947 and 1949). This depends on a coincidence, for in most areas the summer part of E_T is about 90 per cent of the total for the year, and in one or two areas that have been examined in detail the annual E_T for dry years is about 110 per cent of the average. Assuming, as is reasonable, that this small variance in annual E_T is general, then the map can be read as a rough guide to the summer water requirements of crops to ensure maximum growth in drought years. Comparisons with the corresponding rainfalls show that even in average years the potential summer transpiration may exceed the summer rainfall by as much as 6 in. in SE. England : in drought years the deficiency may be 10 or 12 in. Some of this can be supplied by water held in the soil at the end of winter, the amount depending on the depth of rooting of the crop. As a guess, based on very limited experience, the end-of-winter reserve of available water under grassland may amount to the equivalent of four inches of rainfall, so that in SE. England in most years up to two inches of irrigation would augment hay and silage for winter keep and increase summer milk production. In 1949, the second year of controlled irrigation of sugar beet (for an account of the first year's experiment see Penman 1949b), maximum yield was obtained with 6·5 in. of irrigation during the four months mid-May to mid-September, calculated on the assumption of an available soil water reserve of 3 in., an estimated transpiration of 14 in. and a measured rainfall of 4·5 in.

8. Conclusions

(1) The theoretical estimates of natural evaporation based upon weather data can be used to give reliable information about average annual values of evaporation over the British Isles. They can now be used with greater confidence for hydrological and agricultural use, not only for annual averages but also for particular years and for shorter periods within years.

(2) The general standard of rain and river gauging — where the latter exists at all — is reasonably satisfactory. Where losses from catchments occur other than by evaporation and run-off the amounts appear to be small.

(3) Conclusions (1) and (2) stand or fall together.

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The significance of vertical stability in synoptic development

By E. J. SUMNER
Meteorological Office, Dunstable

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SUMMARY

The connection between the development of depressions and anticyclones and the degree of vertical stability of the atmosphere is examined. It is concluded that in middle latitudes the damping due to stability is not important in the largest-scale circulations of diameter greater than about 2,000 km, but has controlling significance for systems of diameter less than about 1,000 km. The difference in the rate of development between an ordinarily stable and a neutral atmosphere may be ten-fold or more for the smaller systems. A very small degree of instability in depth will permit small-scale cyclonic development to proceed rapidly.

Furthermore, the damping effect of atmospheric stability is inversely proportional to the square of the Coriolis parameter. At 10° latitude, for example, the effect becomes dominant for all practical diameters, and it would appear difficult for cyclones or anticyclones of any reasonable size to develop significantly in low latitudes, with the exception of cyclones in a vertically unstable atmosphere.

1. INTRODUCTION

In recent years dynamical principles have been widely introduced into practical forecasting, as, for example, Rossby's " long-wave theory " in America, Scherhag's " divergence theory " in Germany, and in Great Britain the related " development patterns " of Sutcliffe. But all these methods derive from the horizontal flow characteristics and give little attention to the vertical structure. It is no doubt generally accepted that vertical stability exerts a damping effect on the development of circulations in the vertical, and so upon the development of anticyclones and depressions. That vertical instability and convection may generate depressions is also a very old idea in meteorology. These dynamical principles do not however appear to have been discussed in a way which is helpful to the practical forecaster and we are left with rather unsatisfactory pronouncements. Thus Douglas (1934), in considering the problem of rainfall and having shown that the rainfall of depressions is not in general due directly to vertical instability, remarked that " it does not follow that the lapse rate is not an important factor when considered over a large area. There is indeed almost no doubt that it is important." Twelve years later Houghton and Austin (1946), having studied the relation between depressions and lapse rates, stated : " It is evident that cyclonic systems and cyclonic developments were accompanied by lapse rates approaching the moist-adiabatic and usually, but not always, by high relative humidity. In some cases it appeared that the track of the cyclone was influenced by the stability and moisture pattern, that is, the cyclone often appeared to move into regions of existing large lapse rate and moisture content. However, the data do not give evidence that large lapse rates or high moisture content are *a priori* conditions for cyclonic developments. In many cases it appeared just as reasonable to assume that the cyclonic activity produced the large lapse rate and moisture content." Later the same authors add : " In spite of the inconclusive results obtained it still appears that vertical stability

must play a role in cyclonic development." More recent work by Austin (1947) seems equally inconclusive.

A preliminary study of all depressions within the British radio-sonde network (including weather ships on the Atlantic) during November and December 1948 revealed very few cases of even slight degrees of conditional instability in the warmer air, although there was some evidence, in all cases of moderate or rapid deepening (more than 15 mb/day), of high moisture contents over considerable depths accompanied by near-neutral stability. Waves which failed to deepen, or deepened little, were usually associated with dry air or with marked stability, sometimes inversions, above the moist layers.

This brief study confirms the conclusion that deep vertical instability is not necessary for cyclone development, that it is indeed not even a normal accompaniment, but there may be exceptions of importance. In October 1945 a depression deepened from 1,000 mb on the 23rd to 964 mb on the 26th. It moved slowly north-east across the British Isles on the 24th, becoming stationary just off the east coast of Scotland, and was reinforced by another centre on the 25th. The occasion was marked by saturated air and near neutral stability up to the stratosphere and over a wide area. The depression centre passed over Leuchars on the evening of the 24th, having deepened to 968 mb ; both the 0500 hr and 1100 hr radio-sonde ascents showed the air to be unstable and saturated to 350 mb. The 1700 hr ascent showed even more marked instability although the depth of the warm air was considerably reduced by the lifting of the frontal surface and the lowering of the tropopause. The horizontal thermal pattern was slightly developmental in Sutcliffe's sense but not to any remarkable degree. The suggestion is that vertical instability in depth may be a necessary factor in some cases of peculiarly rapid and intense development.

Perhaps we may summarize the position by saying that synoptic meteorologists recognize that depressions are commonly associated with low vertical stability (more rarely with actual instability), and that, although this may be largely a consequence of the cyclonic development, it is also a factor favouring such development. The object of this paper is to attempt some further clarification. We begin by considering the damping effect of stability on large-scale circulations and pass then to the case of instability.

2. The damping effect of stability

In order to permit of a quantitative discussion of the effect of vertical stability on the general development of anticyclones and depressions it is necessary to formalise the problem and we follow Sutcliffe (1939 and 1947) and Charney (1948) in taking as the model a three-dimensional convergence-divergence system. For example, "cyclonic development" is represented by low-level convergence almost balanced, hydrostatically, by upper divergence located mainly in the upper troposphere (since the tropopause normally subsides). There is a middle level of non-divergence p_1 (and maximum vertical motion) which Charney (1947) takes as at about 600 mb. Schematically the circulation is represented by the section in Fig. 1. Anticyclonic development may be represented by a similar model, *mutatis mutandis*.

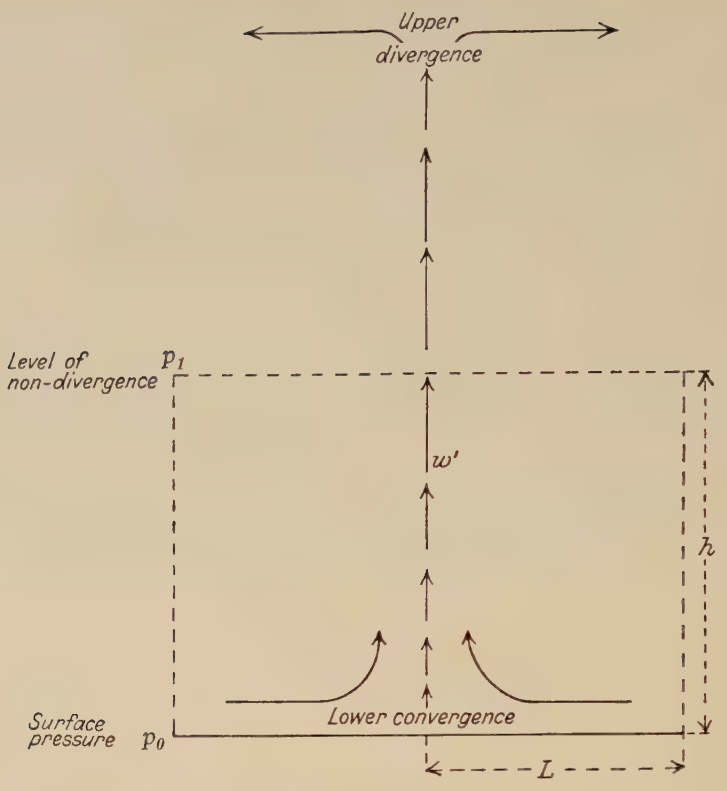

Figure 1. Vertical cross-section of the model of cyclonic development. The distribution of convergence (divergence) changes linearly with height and decreases sinusoidally from a maximum at the centre to zero on a circle radius L.

It is convenient to take Sutcliffe's (1947) expression for the difference in divergence between the two pressure levels p_0, at the surface, and p_1 ($p_0 > p_1$). Then D, the relative divergence (the surface convergence in the case of the above cyclonic model), is given by

$$lD = -\mathbf{V}_1 \nabla_p(\zeta_1 + l) + \mathbf{V}_0 \cdot \nabla_p(\zeta_0 + l) - \frac{g}{l} \nabla_p^2 \left(\frac{\partial h}{\partial t}\right)_p \quad . \quad . \quad . \quad (1)$$

where $\mathbf{V}_0$, $\mathbf{V}_1$ are the horizontal wind vectors and ζ_0, ζ_1 the corresponding vorticities at the levels p_0 and p_1 respectively ; h is the vertical thickness of the layer from p_0 to p_1, and l is the Coriolis parameter.

The function $\frac{g}{l^2} \nabla_p^2 \left(\frac{\partial h}{\partial t}\right)_p$ represents the isallobaric divergence effect of the thermal changes in the air column, and atmospheric stability enters into it by virtue of the dynamical (adiabatic) changes of temperature due to vertical motion. The derivative $\left(\frac{\partial h}{\partial t}\right)_p$, the thickness tendency, may be more conveniently expressed by a slight modification of the analysis of Sutcliffe and Godart (1942) in the form

$$\left(\frac{\partial h}{\partial t}\right)_p = -\overline{\mathbf{V}}.\nabla_p h - \frac{R}{g}\int_{p_1}^{p_0} \Gamma_p \frac{dp}{dt}\, d(\log p) \quad . \quad . \quad (2),$$

in which $\overline{\mathbf{V}}$ is a vector mean velocity approximately equal to the logarithmic mean, R is the gas constant and Γ_p $(=\gamma_p - \gamma_p{}^*)$ is the departure of the actual lapse of temperature (γ_p) referred to a pressure scale $\left(i.e.\ \frac{\partial T}{\partial p}\right)$ from $\gamma_p{}^*$ the wet- or dry-adiabatic lapse rate, whichever applies ; Γ_p is positive for instability and negative for stability. Sutcliffe (1947) has discussed the advectional part of $\left(\frac{\partial h}{\partial t}\right)_p$; we are now concerned with that part due to dynamical temperature changes, *viz.*, the second term on the right of Eq. (2), and we represent the component of relative divergence due to this term by D_s. Substituting for $\left(\frac{\partial h}{\partial t}\right)_p$ in Eq. (1) and following Sutcliffe's treatment (1947, section 9) with little departure, we obtain

$$D = -\frac{v'}{l}\frac{\partial}{\partial s}(l + \zeta_0 + \zeta_1) + \frac{R}{l^2}\int_{p_1}^{p_0}\left\{\nabla_p{}^2\left(\Gamma_p \frac{dp}{dt}\right)\right\} d(\log p) \quad . \quad . \quad (3),$$

where $\frac{\partial}{\partial s}$ represents differentiation in the direction of the shear vector $\mathbf{V}'$ whose absolute magnitude is given by v'. Alternatively we may write

$$D = D' + D_s \quad . \quad . \quad . \quad . \quad . \quad (4),$$

in which D' is the relative divergence due for the most part to the shearing advection of vorticity and the advectional distortion of the thermal field, and D_s to the field of vertical motion and atmospheric stability. The latter may be put in the form

$$D_s = \beta\, \nabla_p{}^2\left(\overline{\Gamma_p \frac{dp}{dt}}\right) \quad . \quad . \quad . \quad . \quad . \quad (5),$$

where β is a constant, and the bar over the product term denotes a mean value taken vertically throughout the layer in question with respect to a logarithmic pressure scale. This factor will contain irregularities due to horizontal variations of stability, which may become large at air-mass discontinuities or at the boundaries between cloudy and cloud-free air. However, we are only concerned here with the broader features of the development of pressure systems and such complexities will be left out of consideration. The effect in question may be called the *field-stability effect*, the word " field " referring to the field of vertical motion† for the limited model adopted although a wider connotation may be attached to the expression so as to include other possibilities.

Developing pressure systems have a maximum of vertical motion in the vicinity of their centre, and in a stable atmosphere D_s is obviously of opposite sign to the

† In this connection it should be remarked that it is the vertical velocity (w') relative to (moving) isobaric surfaces that is significant in producing dynamical temperature changes. This is easily shown to be equal to $\frac{\partial z}{\partial p}\frac{dp}{dt}$, z being the vertical height co-ordinate, and the product $\left(\Gamma_p \frac{dp}{dt}\right)$ may be expressed in terms of the more familiar lapse of temperature with height $\left(\gamma = -\frac{\partial T}{\partial z}\right)$ and this vertical velocity component, since $\Gamma_p \frac{dp}{dt} = \Gamma \frac{\partial z}{\partial p}\frac{dp}{dt} = -\Gamma w'$, where $\Gamma = \gamma - \gamma^*$, γ^* being the wet- or dry-adiabatic lapse rate. However, we prefer to keep to isobaric co-ordinates throughout in the above analysis.

actual relative divergence D ; it is a damping term opposing the development both for cyclonic and anticyclonic development. Eq. (4) may be interpreted as meaning that the actual relative divergence D is compounded of a primary term D' which is reduced by the damping effect of stability D_s, and it is appropriate to write $D(1-D_s/D)=D'$, where D_s/D is the damping factor. Thus, in order to obtain the actual divergence, the primary effect has to be reduced by the positive factor $1-D_s/D$. The magnitude of the damping factor is clearly of great significance. Where it is small compared with unity, development may proceed freely at the full value given by the other terms : where it is large, development will be retarded and may be radically affected. We proceed then to obtain a numerical estimate of this factor.

The model adopted (*e.g.*, Fig. 1) consists of a symmetrical field of low-level divergence (or convergence) decreasing sinusoidally to zero at a distance L from the centre and changing linearly with height, with opposing convergence (or divergence) in the upper levels. It is shown in the appendix that $D_s/D=A\Gamma_p/l^2L^2$, where A is a positive constant depending on the level of non-divergence. This numerical factor is of course applicable only to the idealised model but it is a convenient index, and it is instructive to construct Table I showing the value of the ratio D_s/D in terms of the stability parameter Γ and L, the radius of the system. The table is computed for the 1,000-600 mb layer, taking $l = 10^{-4}$ sec^{-1}, appropriate to middle latitudes. All of the values given in the table are, of course, negative for stability.

TABLE I. VALUES OF THE STABILITY DAMPING FACTOR D_s/D, APPROPRIATE TO MIDDLE LATITUDES ($l = 10^{-4}$ sec^{-1})

Radius of the system.	Γ_p expressed as a fraction (α) of the dry-adiabatic lapse rate.				
km	0·4	0·2	0·1	0·05	0·025
50	176	88	44	22	11
100	44	22	11	5.5	2.8
200	11	5·5	2·8	1·4	0·7
400	2·8	1·4	0·7	0·35	0·18
800	0·7	0·35	0·18	0·09	0·05
1600	0·18	0·09	0·05	0·02	0·01

In general, in the absence of saturation, α, the proportionate departure of the lapse rate from the dry-adiabatic, is equal to or greater than 0·2. It is concluded therefore that the effect of stability is always small for systems of radius greater than say 1,000 km ; in other words the developments of the large cyclones and anticyclones of the broad circulation pattern are not significantly affected by the degree of vertical stability of the atmosphere. With smaller dimensions the effect does however become important. Taking for example a small system of radius 200 km, the damping effect in an ordinarily stable atmosphere ($\alpha = 0{\cdot}4$) is 11 times greater than the resultant development ; in other words the development produced by a given distribution of thermal vorticity (on Sutcliffe's theory) must be reduced more than tenfold in an ordinarily stable atmosphere but would have its full value

in an atmosphere of neutral stability. The implications are very important. If we are dealing with systems of small size, radius 400 km or less, vertical stability must be taken into account and should be given considerable weight by the forecaster. It would seem that very small systems could hardly develop at all in a stable atmosphere. This would virtually eliminate small anticyclones and allow small depressions to develop significantly only where the lapse rate approached the neutral value. This would be restricted almost entirely to the neutral stability of saturated air with a wet-adiabatic lapse rate. However, it should be pointed out that the damping factors are approximately halved for a level of non-divergence of 700 mb, and are reduced to less than a quarter of the values given in the table for $p_1 = 800$ mb. Since, at least in the case of the development of a cyclone, the system is likely to be limited initially to a comparatively shallow depth, the damping may not become really effective until a later stage of growth is reached.

The stability damping factor is inversely proportional to the square of the sine of the latitude so that at 10° lat. it would be 16 times greater than the values given in Table I, or the same values would be appropriate to systems four times larger in radius. It is then clear that with ordinary stability, $\alpha = 0{\cdot}4$, tenfold or greater reduction of the rate of development, by stability damping, would apply to all systems up to 800 km radius. It is not surprising that the development of both cyclones and anticyclones, as we know them in middle latitudes, is virtually impossible in the tropics, excepting the case of instability in depth which would permit of vigorous small-scale cyclone development as we see in the next section.

3. The case of vertical instability

Lapse rates in excess of the dry adiabatic are virtually unknown in deep layers away from the earth's surface, and we shall only be concerned in this section with cyclonic development and the instability with respect to saturation which can only arise in cases of cyclogenesis. Formally, instability in depth can be represented by taking Γ in the previous section as negative. Table I still holds but the field-stability effect no longer inhibits development ; it is now a positive developmental factor with a relative magnitude varying inversely as the square of the horizontal dimensions of the system.

If however we consider as before an equation of the form

$$D = D' + D_s$$

we cannot regard D' as the primary dynamical effect if D_s is of the same sign and greater than D. Evidently the equation can exist in this case only if other dynamical processes oppose the development. The development, now convectively driven, must proceed rapidly, and we may infer that a small-scale cyclone will result, but it is clearly impossible to discuss the problem further in terms of Eq. (1), or any other which is based on quasi-horizontal, frictionless motion. We do not attempt here to pursue the theory of the instability vortex but there is every justification for supposing that tropical cyclones and a number of small hurricane-like centres which develop in higher latitudes, are the result of true instability in depth *i.e.* saturation with a lapse greater that the saturated-adiabatic through a deep

layer. Such a situation will not readily arise as the instability is likely to be relieved by large-scale turbulent mixing before instability develops generally and in depth. Probably a situation in which the instability is latent and realised by the general convergence and ascent associated with a particular cyclogenesis is the most likely origin of deep instability. The abnormal deepening, which occasionally causes depressions in middle latitudes almost to take on the aspect of tropical cyclones is peculiarly difficult to forecast, as would be expected since a very small value of α — a very limited crossing of the threshold of neutral stability — is adequate to give D_s a controlling significance, as is seen from Table I.

4. Comments and conclusions

It will be obvious that the above thesis has several shortcomings. The model adopted is admittedly very crude ; apart from the rigid constraints adopted the complete omission of frontal discontinuities, at least in the case of cyclonic development, imposes a serious limitation. No less important perhaps is the treatment of the terms of Eq. (3) as independent when in fact they are not. It is obvious that the vertical motion associated with a developing pressure system will produce systematic changes in the thermal field and so react on the entire field of development, but it is felt that the instantaneous effects are sufficient to elucidate the general importance of the physical principles involved.

The main conclusions may be summarized as follows :—

(1) A stable atmosphere exerts a damping effect on the development of both cyclones and anticyclones, which is directly proportional to the mean stability and inversely proportional to the square of the horizontal dimensions of the pressure system and to the sine of its latitude (the Coriolis parameter).

(2) It follows that with average stability small circulations (radius 200 km) can hardly develop in middle latitudes and that for free development the radius should approach 1,000 km. For larger systems stability damping is unimportant, *e.g.* for the general circulation cells or long waves.

(3) It also follows that the development of the smaller systems (radius less than about 500 km) is highly sensitive to the degree of stability.

(4) In low latitudes stability damping is relatively much more important, so much so that the only free development in the tropics must be of small-scale cyclones in unstable air.

(5) With a very small degree of general instability the situation becomes highly developmental and small-scale cyclones may be expected to form rapidly ; hurricane centres probably originate in this way.

The criterion is saturation and a slight degree of instability in depth rather than marked instability originating in a limited layer.

5. Acknowledgment

I am indebted to the Director of the Meteorological Office for permission to submit this paper, and to Dr. R. C. Sutcliffe for substantial help in the writing

as well as for many constructive suggestions and criticisms during its preparation. In particular, the emphasis on the size factor was due to him. I am also grateful to Dr. A. G. Forsdyke for help and encouragement throughout.

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Appendix

Estimation of the damping factor

The field-stability term is given by

$$D_s = \frac{R}{l^2} \nabla_p{}^2 \int_{p_1}^{p_0} \Gamma_p \frac{dp}{dt} d(\log p).$$

The average over-all effect on a developing system may be estimated by treating the stability as a constant equal to its mean value over the entire field. Also, integrating the Godart equation of continuity (see Sutcliffe 1947) we get $\frac{dp}{dt} - \frac{dp_0}{dt} = \int_p^{p_0} \mathrm{div}_p \mathbf{V}\, dp$. To a first approximation $\frac{dp_0}{dt}$ may be ignored by comparison with $\frac{dp}{dt}$, therefore

$$D_s = \frac{R\Gamma_p}{l^2} \nabla_p{}^2 \int_{p_1}^{p_0} \left\{ \int_p^{p_0} \mathrm{div}_p \mathbf{V}\, dp \right\} d(\log p)$$

Now, in accordance with the general scheme we have adopted the isobaric divergence may be conveniently expressed by the equation $\mathrm{div}_p \mathbf{V} = \Psi(x, y)\phi(p)$, and if in addition we take $\phi(p_0)$ equal to unity, then Ψ represents the field of divergence at the surface. Also, since p_1 is the level of non-divergence, $\phi(p_1) = 0$. The required damping factor is thus given by

$$\frac{D_s}{D} = -\frac{R\Gamma_p}{l^2\phi(p_0)} \frac{\nabla^2\Psi}{\Psi} \left[\int_{p_1}^{p_0} \left\{ \int_p^{p_0} \phi(p) dp \right\} d(\log p) \right]$$

Assuming for the sake of numerical estimation, a linear distribution of divergence with height, *i.e.* $\phi(p) = \frac{p - p_1}{p_0 - p_1}$ $(p_0 > p_1)$, the integral may be evaluated exactly. Also if the horizontal field of divergence is sinusoidal with respect to x and y, *i.e.*

$\Psi(x, y)$ is proportional to $\cos\frac{\pi x}{2L}\cos\frac{\pi y}{2L}$, where L is the radius of the cell, we find that

$$\frac{D_s}{D} = \frac{R\pi^2\Gamma_p}{2l^2L^2}\left\{\tfrac{1}{2}\frac{p_0(p_0-2p_1)}{(p_0-p_1)}\log\frac{p_0}{p_1} - \tfrac{1}{4}(p_0-3p_1)\right\} = \frac{A\Gamma_p}{l^2L^2} \text{ (say).}$$

It will be convenient to evaluate this for the layer from $p_0 = 1{,}000$ mb, to $p_1 = 600$ mb ; R is equal to 2.87×10^6 cm^2 sec^{-2} deg^{-1}, and if Γ_p is expressed as a proportion α of the dry-adiabatic lapse rate, then

$\frac{D_s}{D} = -\frac{1{\cdot}09\alpha}{l^2L^2} \times 10^{-2}$, where α is positive for stability and negative for instability.

For p_1 equal to 700 mb, the corresponding numerical factor is 0·56, and for a level of non-divergence of 800 mb it is only 0·23.

551.589.1 : 551.583

Types and spells of weather around the year in the British Isles: Annual trends, seasonal structure of the year, singularities

By H. H. LAMB
Meteorological Office, Dunstable

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SUMMARY

From a classification of 50 years' daily weather maps (1898 — 1947) the outstandingly long spells of weather, lasting over 25 days, have been picked out. Frequency curves show the occurrences of these long spells on each day of the year and also the occurrences of each of the seven defined weather-types individually. This leads to a suggested division of the year into five periods, to be considered as natural seasons, and appears to support the definition of more numerous shorter seasonal phases or episodes (singularities). Good correspondence is found with the long-year daily or weekly mean figures of pressure, temperature, rainfall, sunshine, etc. The significance of these phenomena, their dependability as regards date and their secular persistence are discussed.

1. INTRODUCTORY

Soon after the formation in 1948 of the Forecasting Research Division of the Meteorological Office at Dunstable, the unit was fortunate to be presented by Captain Levick (R.E. retired) with the results of a classification of each day's weather map of the NE. Atlantic region surrounding the British Isles and including the seaboard of Europe for the fifty years 1898 — 1947 according to six of the types (AC, W, NW, N, E and S) which we shall define.

The curves presented in this paper show the varying frequencies of occurrence on each day of the year of these different types of weather pattern, and of long spells defined in terms of them.

To the material which came to hand in this way the writer has added a further classification, in which the cyclonic type (C) has been introduced. The frequency curves for this type therefore represent an alternative classification of certain days' weather maps.

We shall find that consideration of the frequency curves brings out a number of evident seasonal trends, which we may use to define certain " natural seasons." A still finer subdivision of the year into rather over twenty shorter seasonal phases or episodes, agreeing with known singularities (recurrent features) in the annual cycle of weather in Europe, also seems to be suggested.

Finally we shall seek to bring these facts into their right perspective with previous work and existing knowledge. Statistical work of this kind does not lead to positive forecasts of the weather on a particular day in a given year, any more than one would say that a particular day will be sunny and warm merely because it falls in summer ; but it may nevertheless be a reasonable and sound guide to the wisest choice of dates for activities that have to be planned long in advance. Our chief object however will be to gain knowledge of the more detailed structure of our climate and to look for pointers to a fuller understanding of the underlying causes and processes at work over the hemisphere at large.

The field we shall enter has been extensively explored in recent years by a number of German workers ; and the concept of singularities, which emerged from their study, has been introduced to English readers by Brooks (1946) who added a good deal of work of his own. Nearly a century ago some of the ground was broken by Buchan (1867) and later by Mossman (1896) in this country. Comparison of Buchan's and Mossman's results with later work, including our own, opens the inquiry to indications of persistence of the phenomena described over far longer periods of time than the fifty years from which our investigation starts.

It must be admitted that much of what we shall discover has long been more or less clearly known by countrymen in this and other lands, though the knowledge became confused and unacceptable to science largely through the reports of travellers, who mistakenly tried to apply these " rules " of sound experience in other localities than those to which they belonged. It must be our hope ultimately to be able to interpret all the more or less regularly recurring seasonal features of the weather in this part of the world in their proper setting as intelligible manifestations of the natural seasonal shifts of activity in the general circulation of the atmosphere. This interpretation, however, lies somewhat beyond the scope of our present inquiry.

2. Type definitions and choice of classification

The weather over the British Isles and surrounding regions was classified according to the seven types (AC, C, W, NW, N, E and S) defined below for each day of the fifty years 1898 to 1947. Out of the 18,261 days covered, 120 (or about two-thirds of one per cent) were considered unclassifiable.

AC. *Anticyclonic type.* Anticyclones centred over, near, or extending over the British Isles ; therewith also cols situated over the country, between two anticyclones. *Mainly dry with light winds (though thunder often occurring in cols in summer). Usually warm in summer, cold or very cold in winter ; mist and fog frequent in autumn.*

C. *Cyclonic type.* Depressions stagnating over, or frequently passing across, the British Isles. *Mainly wet or disturbed weather, with very variable wind-directions and strengths. Usually mild in autumn and early winter, cool or cold in spring, summer and (sometimes) in later winter. Both gales and thunderstorms occur.*

W. *Westerly type.* High pressure to the S. (also sometimes SW. and SE.) and low pressure to the N. of the British Isles. Sequences of depressions and ridges travelling E. across the Atlantic. *Generally unsettled or changeable weather, usually with most rain in the N. and W. districts of the British Isles. Winds shifting rapidly between S. and NW., occasionally SE. or even E. for a short time. Cool in summer, mild in winter with frequent gales.*

NW. *North-westerly type.* Azores anticyclone displaced NE. towards the British Isles or N. over the Atlantic west of our coasts, or with extensions in these directions. Depressions (often forming near Iceland) travel SE. or ESE. into the North Sea and reach their greatest intensity over Scandinavia or the Baltic. *Unsettled or changeable weather, particularly in N. and E. districts of the British Isles, sometimes with fresh or gale-*

force winds between W. and N. The warm sectors may contain unstable air in late winter and spring. Cooler than the westerly type and milder than the northerly type.

N. *Northerly type.* High pressure to the W. and NW. of the British Isles, particularly over Greenland, and sometimes extending as a continuous belt S. over the Atlantic Ocean towards the Azores. Low pressure over the Baltic, Scandinavia and the North Sea. Depressions move S. or SE. from the Norwegian Sea (sometimes having formed in the Iceland -Jan Mayen region, sometimes having come through from farther north, sometimes having entered the Iceland-Jan Mayen region by way of a col near S. Greenland). *Cold, disturbed weather at all seasons, especially in E. and N. districts. Snow and sleet common in winter ; also associated with late spring and early autumn snow on high ground in the N. and with late spring frosts in all districts. The onset of northerly type weather is often accompanied by high winds.*

E. *Easterly type.* Anticyclones over, or extending over, Scandinavia and towards Iceland. Depressions circulating over the western North Atlantic and in the Azores-Spain-Biscay region. *Cold in autumn, winter and spring ; sometimes intensely cold in southern districts and suitably exposed localities elsewhere, with occasional snow in the S. and snow or sleet showers in E. and NE. districts ; fine in the W. and NW. Warm in summer, sometimes thundery. Very dry weather in western districts, relatively dry in many or most other districts.*

S. *Southerly type.* High pressure covering central and N. Europe. Atlantic depressions blocked west of British Isles or travelling N. and NE. off our western coasts. (Seems less persistent than the other types, occurring mainly as occasional variations within spells that are predominantly either westerly or easterly ; very rare in summer.) *Warm and thundery in spring and summer, mild in autumn. In winter mild or cold according as the airmass carried over the British Isles is oceanic or continental in origin.*

The type here defined as westerly has been variously described as westerly or south-westerly in meteorological literature and popular usage.

For the cyclonic type the criterion used was that a depression should be centred, or its central isobar on a 4- to 5-mb spacing should extend, over the mainland of Britain or Ireland. Small cyclonic features were overlooked if over half the country were under anticyclonic influence ; such features are common in the cols when the general type is classified as anticyclonic. Further, to reduce the fortuitous element in the occurrence of the cyclonic type, individual days between the passing of separate depressions were counted as cyclonic if the isobars retained cyclonic curvature or the main trough stayed over the country.

The classification was based on the following series of published daily weather maps, by which also the long spells which we shall catalogue were carefully checked :

1898—1899. Danish-German North Atlantic Weather Maps.
1899—1939. U.S. Weather Bureau : Historical Weather Maps.
1939—1948. Meteorological Office Daily Weather Reports (British Section).

Various other classifications and type-categories have been used by other workers, but few have been applied to so long a period of years as that we shall consider.

Our choice of a starting point was actually determined by the formidable amount of groundwork already done by Captain R. B. M. Levick. This classification has, however, certain important virtues. Any classification which gives prominence to the direction of the general windstream automatically takes account of orography, the most important single factor in local weather. Reference to the positions of the nearest stable anticyclones and depression paths relates the types to the general circulation of the atmosphere. The use of a rather small overall number of types has the further advantage of giving large numbers of samples for each type for statistical consideration. Difficulty, of course, arises in borderline cases ; and for some purposes we shall find it convenient to speak of blended and hybrid types.

Levick's six types (AC, W, NW, N, E and S) approximate to those chosen by Bilham (1938) for climatological discussion, and some of them are quite similar to those originally defined by Abercromby (1887).

More elaborate classifications have been suggested and used by various workers. The earliest was that of van Bebber and Köppen (1895), which defined 20 types of weather in Europe arranged according as the main anticyclone lay over the ocean, the continent or the coastline, in a position for northerly weather in Europe or very far away. This classification seems to have been purely geographical in conception and hard to relate to any models of the atmospheric circulation as a whole. A much simpler classification by van Bebber (1897) defined nine types for central Europe in terms of the position of the dominant anticyclones relative to that region, but was only applied to a 10-year series of charts.

A quarter of a century later Gold (1920) produced his now well-known classification of 28 types of weather affecting the British Isles and NE. France over the fourteen years 1905—18 according to the isobaric forms prevailing, arranged in relation to the position and shape of the anticyclones.

Gold's classification has been largely used by Baur (1947) with some amplification and therefore indirectly forms the basis of much work done in the former German institute for long-range forecasting research. Baur has classified 63 years (1881 — 1943) in a manner which apparently resembles that used in the present work, but his results have not yet been fully published. The results so far quoted by Baur seem to confirm many points in the studies which we shall present.

Interesting comparisons may also be afforded by the empirical investigations of Newnham (1925) and Jones (1943).

3. Long spells of weather and natural seasons

(a) *Occurrence and duration of spells*

The occurrence of occasional long spells of weather, marked by persistence of one or another easily recognised and definable type, is a well-known feature of our climate. Such spells commonly determine the prevailing character of a particular season,

For the purposes of long-range forecasting research, we decided to make a catalogue of the long spells during the past half century, 1898 to 1947 inclusive. The list was confined to spells lasting over 25 days and is set out in Appendix A.

It will be seen from the foregoing section that several of the types we have defined presuppose certain day-to-day variations, particularly such as are connected with the passage of individual depressions and anticyclones. Accordingly interruptions not exceeding 3 days have not been considered as ending a spell. This permitted interval corresponds, for instance, to the slowest travelling ridges of high pressure passing across the British Isles in a westerly or cyclonic sequence.

Hybrid types have also been included in the spells listed so long as the historical weather maps showed obvious persistent features. The hybrids generally showed some oscillation towards each of the individual pure types concerned.

In cases of doubt as to the defined limits of any spell, the narrower limits have been preferred.

Figure 1. Duration of long spells : frequency distribution.

Fig. 1 presents the frequency distribution of various durations in the long spells (of all types) listed in the catalogue. Maximum frequencies with spells of about 29 and 45 days are unmistakable. Other peaks are less well marked and therefore of more doubtful authenticity ; spells lasting for periods between 30 and 40 days are however quite a noticeable feature.

The meaning of unexplained periods of this order, occurring at more or less any time of the year, is probably to be sought in the completion of some physical process or chain of processes within one or more of the main cells of the atmospheric circulation affecting the British Isles. The writer has for instance mentioned elsewhere (Lamb 1948) that most stable, quasi-stationary, warm anticyclones seem to require rejuvenation about every 4½ days by the incursion of a new shallow cold airmass in the bottom layers, renewing the subsidence inversion and its shielding

effect from the wastage caused by ground friction. This seems to be an example of a physical process having a natural or preferred time-scale for its completion, which may sometimes be seen to undergo several repetitions until successive shifts of the rejuvenated anticyclone bring the system over a geographical region thermally or otherwise unsuited to its maintenance. There is actually a suggestion apparent in the figures obtained from limited studies of Levick's basic classification of the 50-years' daily weather maps that the frequency distribution of durations of spells of all lengths shows a series of maxima close to multiples of $4\frac{1}{2}$ days. (The actual maxima obtained were about 9, 13, 16-18, 21, 29-31, 34-36, 44-46 and 54-55 days.) The practical implication of any such association between preferred durations of spells and physical processes of this kind is that the approaching breakdown of a long spell should be apparent also from physical reasoning, once we have identified those factors upon which the stability of the most important controlling cells of the atmospheric circulation depends.

(b) *Occurrence by seasons and definition of seasons*

It soon became evident that long spells show a certain grouping according to the calendar, and that some dates of the year come within periods of persistent weather type much more often than others. Frequency curves have therefore been plotted to show the total number of occurrences of any long spell and of long spells of each individual type on every day of the year. These curves are given in Figs. 2-9. For the frequencies of the individual types hybrid spells have been divided up proportionately: for example AC + N + E is counted as one-third AC, one-third N and one-third E for each day of the spell.

The strongly marked peaks in the total frequency curve (Fig. 2) in high summer and autumn, flanked by minima respectively 84 and 71 days apart, correspond to occurrences of long spells which must be liable to give an impression of the character of the entire season. We must notice that our definition of a spell lasting over 25 days with no breaks exceeding 3 days implies, almost *ipso facto*, that a number of these long spells would be preceded by more or less abortive appearances of weather of similar type, separated from the main spell by breaks of 4 days or more. This did indeed happen and also a number of partial or shorter-lived reversions after the end of the main spell.

These peaks in the frequency curve therefore seem to represent a tendency for one or another type of weather (and corresponding circulation pattern) to become stably established during a given season. Presumably some sort of equilibrium between the condition of the atmosphere and of the external agencies affecting it is set up, and any such equilibrium must be threatened with upset when for instance the distribution of warm and cold sources and strong temperature gradients in the earth's surface underlying the atmosphere change radically with the change of season. The autumn peak is so high that October 6th fell within a spell of weather lasting over 25 days in 54 per cent of the years. The summer peak reaches 48 per cent on 28-29 July. The sharpest minimum of the year falls between these peaks, with long spells occurring only in 10 per cent of the years around 9-12 Sept. In only one year (1923) did a persistent spell of weather (W'ly) begin *appreciably before* and continue until *well after* these dates, and even in that year

the spell was nearly interrupted by the Azores anticyclone pushing up towards the British Isles on the days in question. In 1946 a very long summer spell of bad weather (W + C) carried on till nearly two weeks later, until 25/9.

There is a paradox about the early September minimum of long spells in that a well-known maximum frequency of anticyclonic days in the British Isles (according to Brooks's (*loc. cit.*) and Belasco's (1948) definitions, the main maximum of anticyclonic weather in the entire year) falls on or about the same dates. Logically these must either be shorter-lived or travelling anticyclones. Brooks speaks of a succession of high-pressure centres which normally split off from the Azores anticyclone and travel E. across Europe into Siberia, where pressure is increasing, during September.

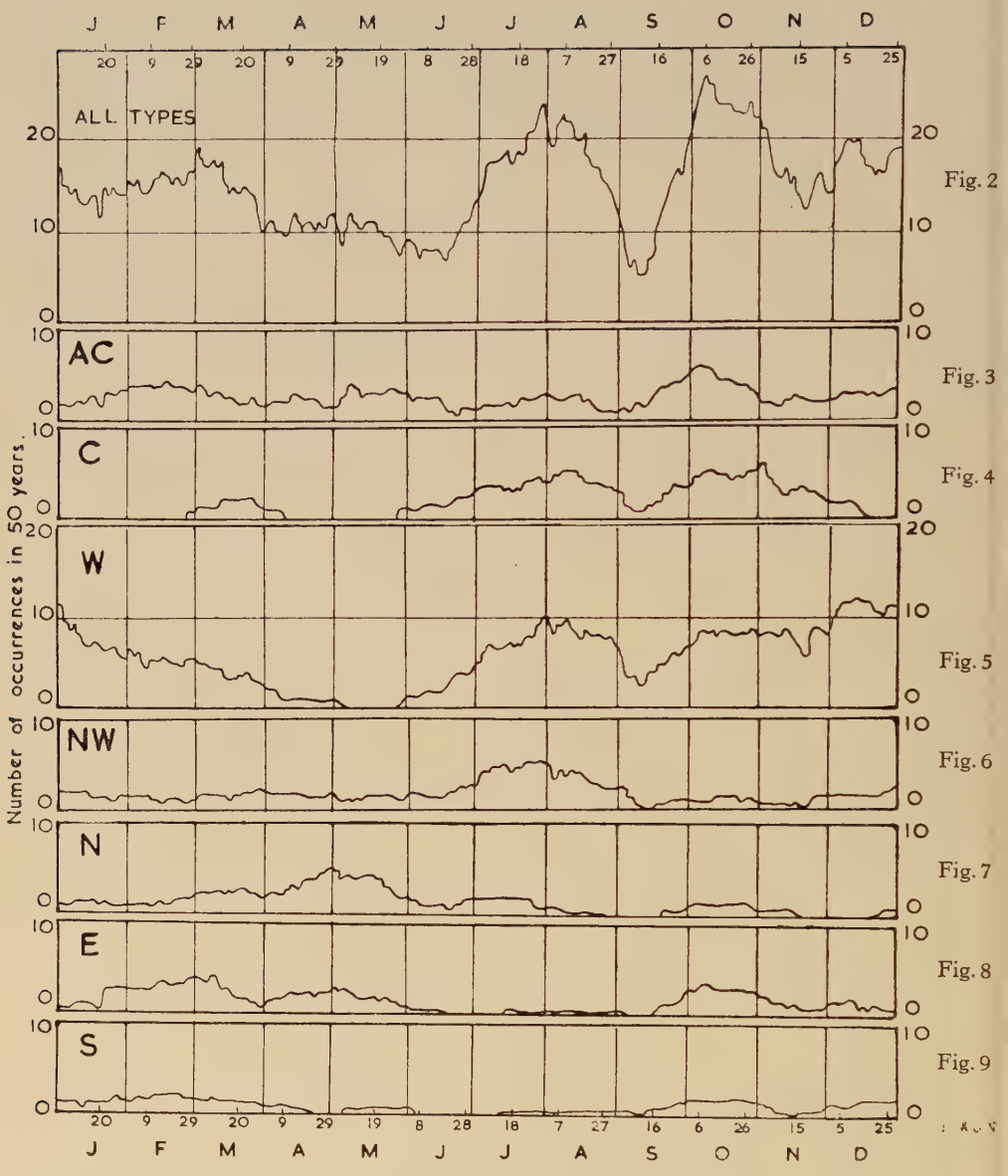
Another curious feature is that both anticyclonic and cyclonic long spells have maxima about the same dates in autumn ; but the frequency of the former falls away during the middle and later part of October, the maximum of the latter extends into November. These correspond to alternative and quite unlike characters of autumn in different years.

There is also a difficulty that the summer and autumn seasons suggested by the two main peaks in the total frequency curve (Fig. 2) are long enough to admit the possibility of the particular season containing two long spells of unlike character in any given year. This important and upsetting occurrence is fortunately rather rare. The ten cases during the 50 years examined are listed in Table IV.

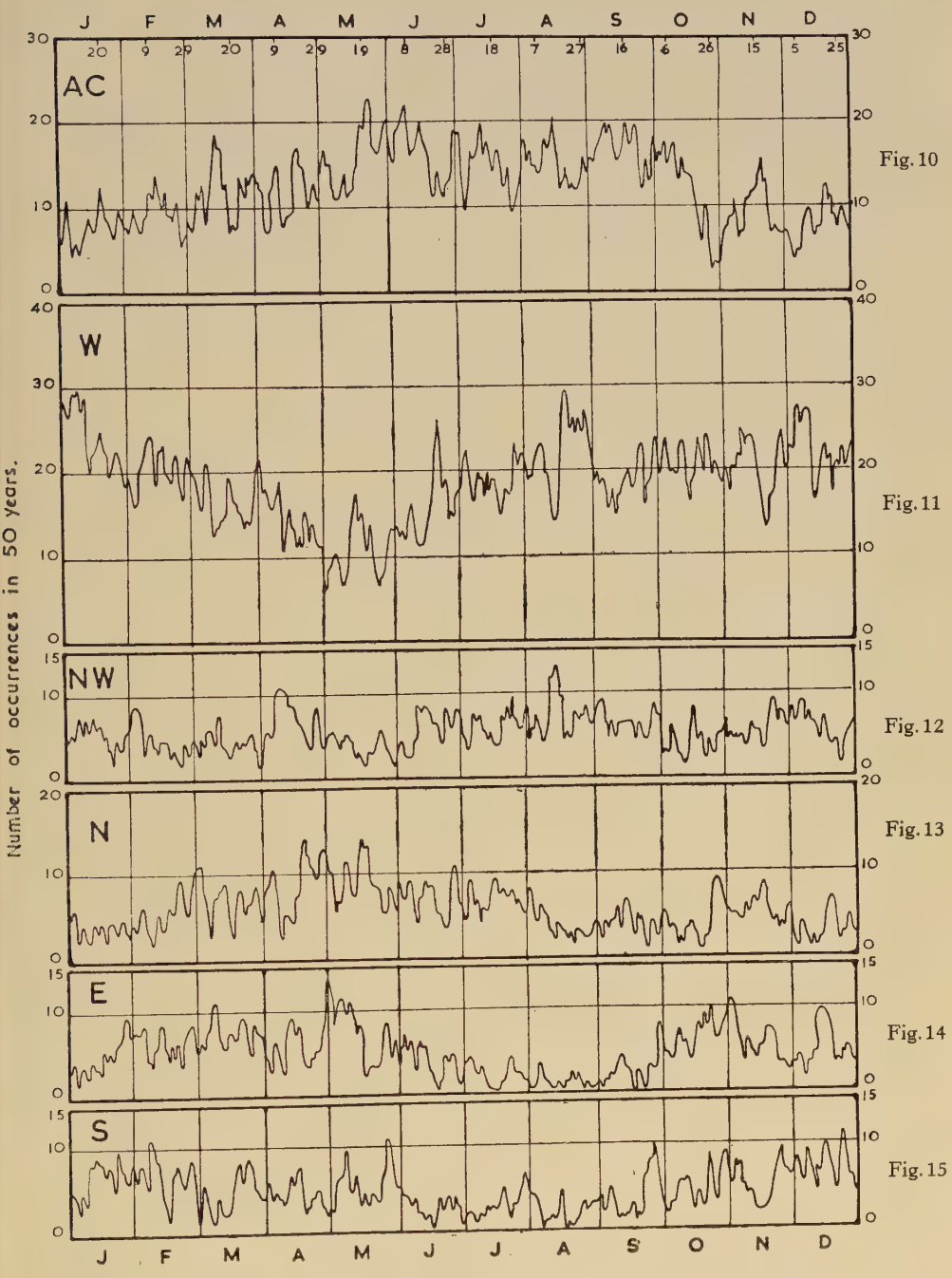
In spite of paradoxes and difficulties such as we have named the frequency curves of occurrences of long spells (Figs. 2—9) can usefully be taken to define a series of five natural seasons of the year, applying at least to the period 1898 — 1947 in the British Isles. If we can relate these seasons, and the circulation patterns observed to become persistent within them, to known external agencies working upon the atmosphere, we may hope to improve our understanding of the longer-period weather processes affecting our country and much of Europe. Definition of the five periods given in Table I, considered as natural seasons, will in any case aid our systematic study of the individual frequency curves and help us to draw lessons from them.

TABLE I. Table of natural seasons

Calendar period (Approx. dates)	Designation	Characteristics used for definition
18 June — 9 September	(High) Summer	Clear maxima and minima (Fig. 2) in the occurrence of long spells mark this period off from the rest of the year.
10 September — 19 November	Autumn	Clear maxima and minima (Fig. 2). The final minimum is less sharp than the initial one.
20 November — 19 January	Fore-winter or Early winter	Moderate maxima and minima in the total frequency curve (Fig. 2), composed of unlike trends in the individual frequency curves (Figs. 3—9) within these dates.
20 January — 29 March	Late-winter, or (in some years) Early spring	Unlike trends in the individual frequency curves and distinctly changed trends from the period before 20 January. A modest maximum in the total frequency curve.
30 March — 17 June	Spring, or (in some years) Early summer	Period of consistently low frequency of long spells, apart from the year's maximum of N.'ly.



Figures 2 to 9. Frequency curves for long spells of over 25 days of persistent weather. 1898—1947.



Figures 10 to 15. Frequency curves for daily occurrences. 1898—1947.

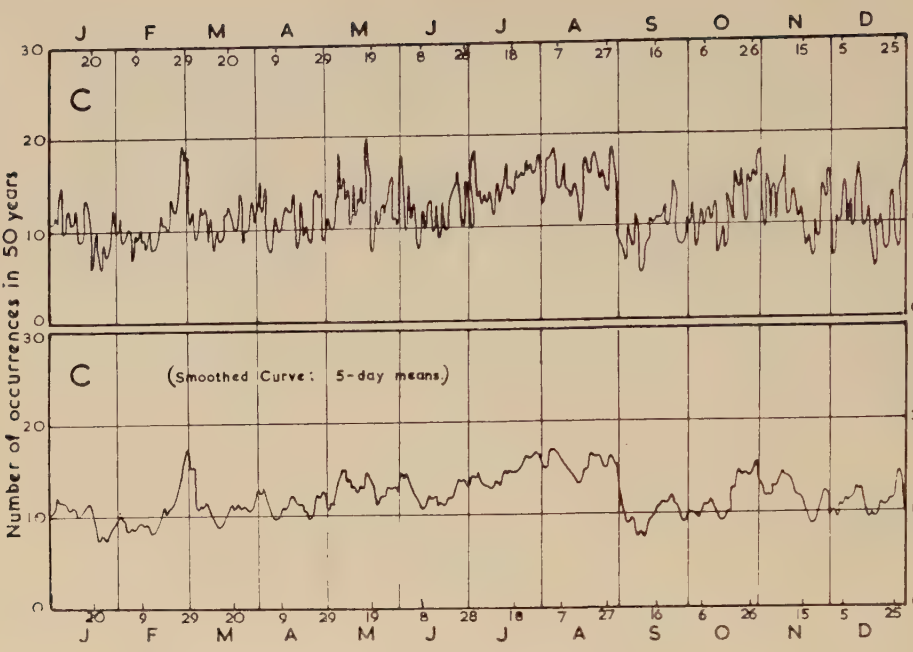


Fig. 16

Fig. 17

Figures 16 and 17. Frequency curves for daily occurrences. 1898—1947.

Table I is given in expanded form in Appendix B with fuller details of the characteristic features of the frequency curves in each season. It will be seen that the summer and autumn seasons are well defined with sharp limits in the general run of years and that the seasons which follow are picked out by progressively more subtle distinctions.

The sharp minimum in the total frequency curve of long spells (Fig. 2) marking the summer-autumn break in early September appears to be punctual to within a week or so in most years. Similarly the features of the same curve which mark the beginning of the high-summer period and the end of autumn (about 18 June and 19 November respectively) are connected with pronounced features of the individual daily frequencies of each type (singularities : see the next sections and Figs. 10 — 17) which have little variability of date in individual years.

The remaining three seasons are less clearly defined. The season-names suggested have been kept as near as possible to the names already in use in the German literature for central Europe, but the variability from one year to another in winter and spring necessitates certain alternative usages in the British Isles on account of their position on the ocean margin. The change from fore-winter to late winter brings in a milder or a colder season in different years ; in the former case it is natural to speak of an early winter and early spring. Finally the late-winter to spring change can hardly be given a definite date ; it is in the nature of a transition achieved by spasmodic advances and reversions. For example, in England it may even happen, as in 1929, that the same anticyclonic spell which gave frost in February brings the first warm days in March. Sooner or later the temperature-rise is checked by one of the northerly situations characteristically occurring in spring.

The seasonal change in January is defined by a somewhat indefinite trough in the curve of total frequency of long spells (Fig. 2) and by a different composition in terms of relative frequency of different types of long spells in the peaks of the curve before and after this point. This is most easily seen by comparing the frequency curves on the one hand of westerly (Fig. 5) and on the other hand of anticyclonic and easterly long spells (Figs. 3 and 8). Westerly long spells were established in over 20 per cent of the years 1898 — 1947 during much of the fore-winter period, whilst anticyclonic or easterly long spells were rare at that time, together only 8 to 10 per cent. In the period after 20 January long spells of anti-cyclonic or easterly type were established in about 15 per cent of the years, long spells of westerly type in only 10 to 12 per cent. (It may be significant that we find this change of trend about the time of a short-term peak (singularity) of anti-cyclonic conditions over Europe.)

The overall frequency of long spells of any type seems to be slightly lower in late winter than in early winter and a good deal lower than in summer and autumn.

Long spells and the type of stability which they imply are clearly at their rarest in spring. We have in fact used this characteristic to define the spring period. The occurrence of long spells of westerly weather (the most numerous individual type in all other seasons) falls to zero. Only northerly spells have an important maximum — their main maximum of the whole year. The weather becomes typically more spasmodic, characterized by less persistence and shorter spells as winter fades into spring. This is the least definite point in the timetable of changes of season in the British Isles in the entire year : in extreme cases late winter has almost from the beginning the character of spring and the best weather of the year may occur in April and May, which are then aptly named early summer ; in other years late winter marks the depth of winter.

The great differences in winter and spring between different years are doubtless associated with differences in the extent and distribution of snow-cover over the continents and of fast ice in the polar seas achieved during the winter. These conditions affect greatly the late-winter cooling in middle latitudes and the patterns and progress of the subsequent spring warming. The autumn and spring (or early summer) seasons are the periods when differences of temperature between continents and oceans in middle latitudes are generally least. At some point of time in autumn, before any deep and lasting snow-cover has been established, we should expect the flow of the zonal westerlies around the world to be at its freest, though distortions may be introduced by the developing snow-cover over Labrador and North-East Asia ; during the spring, while great expanses of snow remain in Canada and Siberia, the flow is frequently meridional and the warming punctuated by northerly outbreaks.

(c) *Secular persistence of the pattern of natural seasons*

Evidence from earlier diarists suggests that the same seasonal pattern, albeit with some changes in the relative frequencies of different types but with periods of change and breakdown about the same dates of the year, has persisted in recognizable form in spite of climatic fluctuations at least from 1660 to the present

day*. If this be so, it may reasonably be expected to have a continuing validity extending beyond our 50-year period into the future.

The most strikingly unfamiliar feature recorded by Pepys is the occurrence of one or two prolonged early-winter frosts in the 1660's. Changes in the relative frequencies of different types are also noticeable in the different decades between 1897 and 1947.

(d) *Annual and seasonal trends of long spells*

Fuller examination of the individual frequency curves (Figs. 3 — 9) for the half century 1898 — 1947 prompts the following notes on the seasonal trends of each type of long spell.

AC (Fig. 3). Long anticyclonic spells may evidently become established over the British Isles at any time of the year, though certain periods are favoured. The frequency curve is similar to that for E. spells with which this type is associated in many hybrids except in summer, when association with NW. is commonest. Belasco has noted (*loc. cit.*) that our summer anticyclones are mostly associated with maritime (Atlantic) air and those of other seasons are more liable to bring continental air-masses.

Pure anticyclonic long spells are not uncommon (24 per cent of all cases involving an AC element), especially during forewinter and spring.

The frequency curve of long anticyclonic spells shows interesting differences from the frequency distribution of individual anticyclonic days, which have already been referred to (p. 399) and may be seen by comparison with Fig. 10.

C. (Fig. 4). Summer and autumn peaks of cyclonic types follow the same trend as the frequency of long westerly spells, but in the other seasons the curves are quite unlike. Even so hybrids W + C are commoner than pure cyclonic long spells at any time of the year.

Simultaneous maxima of C and AC, W and E long spells occur on or about 6-12 October. Apparently alternative and quite unlike patterns of circulation can become established in autumn. Anticyclonic autumns tend however to begin in September and break down during October, whereas cyclonic autumns set in a little later and carry on into November.

W. (Fig. 5). 40 per cent of the long spells involving W were pure westerly, a higher proportion of pure types than with any other type of long spells recognized.

Westerly long spells were also far commoner, whether only pure or hybrid types were counted, than any other type amongst the long spells except in spring. The actual maximum occurred in fore-winter.

The possibility of a long-continued W spell is probably blocked in spring by the frequency of N.'ly polar outbreaks from the Norwegian Sea at this time of year.

NW. (Fig. 6). As in the case of anticyclonic spells, long NW spells can probably occur at any time of the year through a moderate dispacement of the Azores High towards the British Isles. However, their occurrence is uncommon

* For example we read in Boswell and Johnson's "*Tour of the Hebrides*" in 1773 that a long-continued spell of dry weather which dried the Highland waterfalls came to an end about 2 September. Changeable weather followed, but September and October were predominantly wet and stormy in Scotland that year apart from short fine spells 21-25 September and 16-22 October. Boswell adds a disquisition on the usualness of the long rainy season of the year in the Hebrides beginning about that time.

except in high summer. At that season low pressure, "monsoon low," becomes firmly established in some years over Northern and Central Europe and displaced high pressure centres from the sub-tropical Atlantic more rarely continue on the tracks which are common at other seasons across the British Isles into Europe. Baur (1944) writes: "...at the end of July and beginning of August a high pressure centre splitting off... from the Azores anticyclone... can settle down over Central Europe thanks to the already weaker insolation..." The individual daily frequencies of the various types of weather in the British Isles show notably low incidence of types E and S, which correspond to anticyclonic conditions over northern and central Europe, throughout the high summer period. Anticyclones over the British Isles are however not uncommon at that time of the year.

N. (Fig. 7). The concentration is in the first half of the year. The main yearly maximum in spring is clearly associated with outflow of cold air from the Polar Basin by way of the Greenland Sea and Norwegian Sea.

Combinations with E and with AC in hybrid types are far commoner than pure N long spells, the latter being quite rare.

Occurrence of a N'ly element in long spells fell to zero from late November until 20 December. It appears that at this time of year the Atlantic westerlies were always sufficiently strongly developed and penetrated far enough east to block the advance southward over the British Isles of any persistent, strong flow of cold air from the Norwegian Sea or to terminate any northerly outbreaks into the eastern North Atlantic after a few days.

E. (Fig. 8). Long spells with easterly weather occur most commonly in association with the anticyclonic type over the year as a whole and in every season except spring, when associations with northerly weather are even more prominent. This corresponds to the fact that in spring, and to a less extent in late winter, easterly spells are associated with extensions of the Polar Basin anticyclone from Greenland rather than displacement of the Azores High or offshoots from it over NW. Europe. The year's maximum frequency of easterly long spells is only $7\frac{1}{2}$ per cent on 8-12 March.

The frequency distribution is like that of anticyclonic long spells except in high summer. At that season (see under NW above) it is rare or difficult for offshoot centres of the sub-tropical anticyclone to pass on over the British Isles into continental Europe. It does seem possible, however, by way of exception for individual centres of high pressure to become established even in the warmest season over the relatively cool surfaces of the Alps, the Baltic or the Norwegian Sea. (See also reference to occurrences of type E in summer in footnote on p. 409.)

S. (Fig. 9). The rarest of all the defined types amongst long spells, occurring only in hybrids.

Southerly weather in the British Isles is associated with high pressure over continental Europe and therefore virtually missing in high summer.

Combinations with either W, AC or E predominate (43, 23 and 26 per cent. respectively of all long spells containing a S'ly element).

These facts are seen from a slightly different viewpoint in Table II, which sets forth in order of frequency all the pure and hybrid types of long spell which occurred season by season.

TABLE II. Occurrences of long spells (lasting over 25 days) of different types in 50 years (1898 — 1947)

Type of Spell	Occurrences by Seasons*					Total Occurrences
	Summer (1)	Autumn (2)	Fore-winter (3)	Late Winter (4)	Spring (5)	
W	6	6	14	6	0	32
W+C	11	9	4	1	0	25
AC	2	2	3	2	4	13
AC+N+E	0	3	1	3	3	10
AC+NW	5	0	0	3	0	8
AC+E	0	3	2	2	0	7
W+NW+C	5	1	0	1	0	7
W+S	0	0	2	4	0	6
N+E	0	0	0	1	5	6
N+NW	1	0	0	0	4	5
AC+S+E	1	2	0	1	1	5
C	1	3	0	1	0	5
W+NW	3	0	0	0	1	4
W+NW+S	0	1	0	1	0	2
NW	1	0	1	0	0	2
S+E	0	1	1	0	0	2
AC+N	1	1	0	0	0	2
AC+N+NW	0	0	1	0	1	2
AC+W+NW	0	1	1	0	0	2
AC+W	0	1	0	1	0	2
N	0	0	0	0	1	1
E	0	0	0	1	0	1
N+E+C	0	0	0	1	0	1
N+NW+W	0	0	0	0	1	1
N+NW+W+C	1	0	0	0	0	1
AC+N+NW+W	1	0	0	0	0	1
AC+NW+N+E	0	0	0	0	1	1
AC+S	0	0	0	0	1	1
AC+W+S	1	0	0	0	0	1
AC+S+W+NW	0	0	0	0	1	1
W+S+C	0	0	1	0	0	1

*—These five seasons are defined on p. 399.

In all, 158 spells lasting over 25 days appear in the catalogue of 50 years (Appendix A). As we see from Table II, the commonest types of long spell were W (32 cases), W + C (25 cases), AC (13 cases), AC + N + E (10 cases) and AC + NW (8 cases). Spells, including hybrid types, which involved an anticyclonic element (AC) numbered 56 altogether, and spells involving a westerly (W) but no anticyclonic element accounted for 79 of the 158. Spells with depressions passing frequently over the British Isles (*i.e.* involving C) were somewhat less common, amounting to 40 in all.

Notice that only W and AC, and to a less extent C, commonly occur as pure types lasting over 25 days.

W and C spells, and hybrids involving them, predominate when the stable anticyclones are far from the British Isles.

Types which commonly occur when anticyclones are established near the British Isles, are E, N, NW and S ; and any, or all, of these might conceivably

occur as occasional features of one and the same long spell of anticyclonic character. Even W is commonly combined with anticyclones affecting the south and south-east of the British Isles, though this differs from the other cases in not implying any great departure of the anticyclone from the subtropical belt. Table III picks out the commonest types of spell in each season and gives the number of cases in the fifty years 1898 — 1947 of each type singly and arranged in groups according to the broad character of the season.

Cases where a season changed character in the middle, with unlike spells lasting over 25 days early and late in the period, were not common. Those which did occur are listed in Table IV. They are all cases where the first long spell became established very early in the period defined as a natural season.

TABLE III. Commonest long spells in each season

Season and total No. of long spells	Commonest Types
Summer (40 long spells)	W+C 11, W 6, W+NW+C 5, all types involving C or W without AC 24; AC+NW 5, W+NW 3, AC 2, all types involving AC 11.
Autumn (34 long spells)	W+C 9, W 6, C 3, all types involving C or W without AC 20; AC+E 3, AC+N+E 3, AC 2, AC+S+E 2, all types involving AC 13.
Fore-winter (31 long spells)	W 14, W+C 4, W+S 2, all types involving C or W without AC 21; AC 3, AC+E 2, all AC types 8, cold types (E or AC without W) 7.
Late winter (or Early spring) (29 long spells)	W 6, W+S 4, all types involving W without AC or C and without E *i.e.* mild types 14; AC+NW 3, AC+N+E 3, AC 2, AC+E 2, all AC types 12, all types involving E or AC without W or NW *i.e.* cold types 11.
Spring (or Early summer) (24 long spells)	N+E 5, N+NW 4, types involving W without AC 2, cold types, involving N or E without AC 11; AC 4, AC+N+E 3, all AC types 11.

TABLE IV. List of individual seasons of dual character, owing to an important change of type in mid-season

1906	Summer	AC+N+NW+W	till 13 July	W	from 14 July
1910	Summer	N+AC	till 26 July	C+W	from 27 July
1914	Late winter	W+S	till 23 February	W+NW+C	from 28 February
1920	Summer	W	till 9 August	AC+NW	from 10 August
1921	Summer	AC+NW	till 15 July	W+C	from 22 July
1923	Fore-winter	AC	till 11 December	W	from 12 December
1936	Autumn	AC+E	till 11 October	W+NW+C	from 12 October
1939	Fore-winter	W+C	till 11 December	AC	from 13 December
1943	Late winter	W+S	till 15 February	AC+NW	from 17 February
1944	Fore-winter	C+W+S	till 12 December	AC+NW+N	from 23 December

Use may be made of the facts we have here arranged in seeking to identify the underlying workings of those external agencies which are likely to be in some degree determining or limiting factors in every year. If, for example, we are right in identifying the autumn before all others as the season when differences of temperature between continents and oceans in middle latitudes are least important,

and warm and cold waves in the troposphere have their greatest mobility, then the discovery of more or less sharp time limits to the circulation régimes corresponding to this state of affairs is interesting and needs explaining. It suggests that various alternative circulation patterns may become firmly established but that not all intermediate types are possible or capable of becoming stable. One would suppose that a given circulation régime may continue up to a certain point after the optimum geographical or external conditions for it have disappeared, but must ultimately collapse. These speculations may be premature but they indicate one way in which the information laid bare by this investigation might lead on to greater understanding of the seasonal and slower-changing factors at work upon the atmospheric circulation and their probable influence on the weather.

In the meantime the work may also give some immediate guidance to the forecaster, particularly at times when a long spell is becoming established or is threatened with breakdown. The outlook may be more confidently judged in the light of the historical trends of particular types of long-spell stability in the last half century, especially when the date is near a seasonal turning point or when an identified long spell is approaching for instance its 29th or 45th day and symptoms of weakening or breakdown appear.

We shall find that the calendar of individual daily frequencies of the various defined weather-types throws some further light on likely dates for the onset and breakdown of long spells of particular character.

4. Frequencies of individual weather types on individual days of the year

(a) *General*

Frequency curves for the individual daily occurrences of Levick's six types of weather (AC, W, NW, N, E and S) in the British Isles and of our independent classification of cyclonic days (C) are given in Figs. 10 — 17. As the period covered is 50 years, percentage frequencies are obtained simply by doubling the figures for number of occurrences.

The frequencies of cyclonic type show more day-to-day variability than the other curves, doubtless because the existence of a cyclonic centre over the arbitrarily chosen area which interests us is a small-scale detail of the atmospheric circulation and therefore more fortuitous in its occurrence on any given day than the other types, each of which corresponds to a certain broad-scale pattern or *Grosswetterlage* (Baur 1936, 1947) of longer normal duration. Fig. 17 therefore presents a smoothed version of the frequency of occurrence of cyclonic weather over the British Isles, taking 5-day running mean values centred about each successive day. All the seven main peaks on this curve (29 February 35 per cent, 7 May 30 per cent, 2 June 30 per cent, 4 August 35 per cent, 19 August 33 per cent, 28 October 32 per cent and 27 December 30 per cent) are authenticated by peaks of frequency in both the first and second 25 years close to these dates. The same peaks are, with little shift of date, still more pronounced on the unsmoothed curve (Fig. 16) and one further one, also authenticated in both halves of the 50-year period, on 17 May reaches 40 per cent. This is followed by a sharp minimum of 14 per cent only 2 days later, which reduces the prominence of the maximum on the smoothed curve.

In general the frequency curves of the different weather types show distinct annual or seasonal trends, on which pronounced variations of shorter duration about particular dates are overlaid.

We shall first note briefly the annual trends of each type, and then pick out for mention only those pronounced shorter-period variations whose reality or significance as recurrent tendencies about the given date of the year can be vouched for by association with other known events and processes.

(b) *Annual and seasonal trends*

AC. (Fig. 10). The period of greatest frequency lasts from late May until mid-October, with the main maximum (about 40 per cent) about the beginning of this period followed by less frequent occurrences (generally 20-35 per cent) during high summer and a second maximum (30-40 per cent) in September.

The year's minimum (4 per cent) in late October is a typical short-lived but pronounced variation (singularity) associated with particular dates and is followed by other, slightly less pronounced minima (5-10 per cent) early in December and January. Through the winter period of low, but progressively rising, frequency of AC type the long-term trend is hard to detect on account of the pronounced shorter-period variations, of which the maxima on 19 November and 12 March reach 30-40 per cent and intervening maxima on 19 December, 21 January and 14 February are slightly less prominent.

W. (Fig. 11). This, the most frequent of all the types, has maxima about 60 per cent in early January and late August ; though both appear to be connected with shorter-period variations. The frequency runs about 40 per cent through most of the year, but falls off from the January peak to the year's minimum in May (10-20 per cent on individual days). The recovery in June is sharp.

NW. (Fig. 12). Little annual trend discernible. The type occurs whenever anticyclones advance from the Azores towards our coasts or north over the Atlantic. The main maxima on 9-12 August and 6-8 April (20-25 per cent) mark typical short-period variations.

N. (Fig. 13). The year's maximum occurs in April and May, culminating in short-term peaks (about 28 per cent) on 17-19 April and 13 May. The frequency is lowest from August to mid-October and in early December, January and February, though overlaid by short-term variations. Sharp recoveries of frequency are seen in late October and late February, leading up to peaks of 18-22 per cent on 25-26 October and 28 February-3 March.

E. (Fig. 14). The most obvious feature of the annual trend is the long period of very low frequencies (0-8 per cent) throughout high summer, when anticyclones over the heated land surfaces east and north-east of the British Isles are rare.* The frequency of easterly weather rises through September and October to a late autumn maximum, 20 per cent being reached in individual peaks on 22 October and 31 October-1 November associated with a generally cyclonic tendency over

* Jones (*loc. cit.*) found from a study of the 27 years 1896—1910 and 1930—41 that weather characterized by the main high pressure system north of 60° N. was rare in mid-summer but notably persistent when it did occur at that season. This observation probably relates to anticyclones in the Greenland—Norwegian Sea—Scandinavian sector between 60 and 80° N. rather than to the inner Polar Basin, where anticyclonic conditions are by no means rare in summer.

this country. A fore-winter minimum, with a notable short-term interruption in mid-December, is followed by a generally rising frequency of easterly weather from late January to the year's maximum in late April and early May (28 per cent on April 29).

S. (Fig. 15). The annual trend is much less noticeable than the shorter-period variations. The frequency however remains low throughout June, July, August and the first half of September, as would be expected in the season when continental anticyclones are rare and poorly developed ; there is nevertheless some sign of a temporary appearance of southerly weather about the end of July, which we may associate rather with a peak of occurrence of stagnant thundery lows over the British Isles. The frequency of southerly weather is generally higher (10-15 per cent) throughout the colder seasons, all but one (5 May) of the peaks of 20 per cent and over being associated with known singularities when the frequency of continental anticyclones is high (24-25 September, 23 November, 13 December, 21-23 December, 22 January, 6-8 February, 5 May and 26-27 May).

C. (Figs. 16 and 17). Once again the short-term variations are more prominent than the annual trend, which shows however a distinct maximum in late July and August followed by an abrupt fall to one of the year's minima in September. An autumn maximum about the end of October is followed by a decline to the next year's minimum at the time of the January and February anticyclones. There is a sharp recovery to a brief maximum at the end of February.

We have already referred to the seven or eight main peaks of shorter-period cyclonic activity (about 29 February, 7 May, 17 May, 2 June, 4 August, 19 August, 28 October, 27 December) authenticated in both halves of the 50-year period examined. Some of the lesser peaks are almost as well defined.

Study of the daily weather maps suggests that the prominent maxima of cyclonic activity at the end of February and August are incidents in the breakdown of whatever circulation patterns have been stable in late winter and high summer respectively. The maximum on 2 June is plainly connected with the onset of the European summer monsoon described by various authors. The cyclonic maxima in May are generally the end-product of northerly outbreaks. The high frequency of the cyclonic type in July and early August is associated with stagnant, thundery lows over the heated land or with Atlantic depressions slowing up as they pass across the country. The stormy periods with depressions passing across the British Isles at the end of October and just after Christmas are singularities which have been described by Brooks (*loc. cit.*), the former marking the breakdown of many long spells of fine weather in autumn.

(c) *Inferences*

The frequency curves (Figs. 10-17) can be used to search for singularities which may not only help the forecaster but also guide research on problems connected with longer-range forecasting and the atmospheric circulation processes which belong to each season of the year, with its characteristic pattern of thermal distribution, and to each change of season. Indeed some of the shorter-period variations have already forced themselves upon our attention as the most noticeable features of the individual frequency curves.

The curious succession of more or less monthly maxima and minima which, as we have noticed, almost completely mask any smooth underlying annual trend in the frequency curve for the anticyclonic type (Fig. 10) through the winter months corresponds to an alternating sequence of quiet anticyclonic and stormy westerly or cyclonic singularities in winter, which is quite well known. It is reasonable to consider whether this phenomenon can be due to some inherent instability in the middle-latitude westerlies in winter, whereby phases of intense development of the westerlies actually create conditions favouring anticyclogenesis near the western limit of the continental snow-cover. The anticyclones themselves are in turn undermined by cyclonic development accompanying invasions of deeper masses of cold air from the west or north-west, when these are available. This condition may sometimes make it impossible to break down the stability of a late-winter anticyclone which has spread over all the continental area. German writers have referred to the failure, at least in Germany, of the usual sequence of singularities during severe winters, when long spells of anticyclonic and easterly weather are established.

Hardly any of the observed singularities, or more or less regular recurrences in the cycle of our weather around the year, shows itself clearly in every single year, and forecasters are interested in the most dependable ones. Forecasts which pay heed to known singularities stand a better chance of success for that reason ; and if forecasting that one of these known features will not occur in any given year it is well to be specially sure of one's ground.

The next section is therefore devoted to fitting the evidence of our frequency curves into the existing knowledge of short-term singularities, defined as notably recurrent features associated with a rather narrow range of calendar dates, and to seeking an understanding of the significance of this finer seasonal structure of the year.

First, however, we may notice without further comment that the frequency curves for various types of weather in the British Isles show that, given no basic change of climate, certain actual dates carry such a high probability of weather of a given type that a forecast issued half-a-week to a week ahead purely on synoptic methods might not be more dependable than the calendar alone.

The frequency of the westerly type *W* reaches or exceeds 50 per cent on 32 days of the year, *viz.* 1-11 January, 18 January, 20 June, 17-22 August, 24 August, 26-28 August, 8 November, 27 November, 4-9 December, 31 December. The absolute maximum is 60 per cent on 8 January, associated also with a minor peak of depressions centred over the British Isles.

No other type alone reaches 50 per cent on any particular day, although the anticyclonic type *AC* (alone) approaches it with 46 per cent on 21 May, 44 per cent on 7 June and 42 per cent on 15 August.

The anticyclonic and easterly types may however reasonably be considered in combination. Both correspond to anticyclones over, or rather near, the British Isles and clearly outside the subtropical belt ; they commonly occur together in the longer spells of dry, fine weather in this country. The occurrences of either *AC* or *E* considered separately on any given day may in this light be considered more or less fortuitous. The combined frequencies of types *AC* and *E* reach or

exceed 50 per cent of the years on 12 days of the year, namely 29 April-3 May, 21-22 May, 24 May, 30-31 May, 5-6 June.

The further combination $AC + E + N$ corresponds to a real grouping in many long spells of settled fine, dry and generally cool or cold weather in this country, oftenest in late-winter, spring and autumn.* Anticyclonic systems outside the sub-tropical belt wander about over the region Britain—Scandinavia—Iceland—Greenland at these times. The combined frequences of types *AC*, *N* and *E* exceed 50 per cent on many days of the year, notably 7-15 March, 25-29 March, 16-22 April and 25-30 April as well as the entire month of May and first half of June and 25 June-2 July. The peak is 74 per cent on 30 April. There are no such periods of many successive days of high probability of *AC*, *N* or *E* in the second half of the year, though the 50 per cent criterion is just reached or exceeded on 18 September and 19 November as well as on isolated days in October.

One other combination deserves to be considered, namely $AC + S + E$, corresponding to European continental anticyclones which occasionally come over the British Isles. The grouping is a real one in various spells of weather in winter and spring, being associated with dry, fine and cold winter weather over the south-eastern half of Britain. The combined frequencies of *AC*, *S* and *E* are nearly 50 per cent in two periods in winter, 10-24 December and 1-26 February. The peaks of the combined frequencies of $AC + S + E$ are 52 per cent on 12-13 December and 22 December and 50 per cent on 24-25 February.

5. Singularities : a finer seasonal division of the year

(a) *The concept*

Various lists of singularities in Europe and these islands have been drawn up by Schmauss (1938), Flohn (1942), Brooks (1946), Baur (1947, 1948) and others. Unfortunately these lists differ from one another in a number of details on account of the different criteria used to define the phenomena described. Some authors have sought to confine their lists to singularities showing a very high degree of reliability measured by recurrence in 80 to 100 per cent of the years examined ; and it has been possible to achieve this by using sufficiently broad definitions and allowing a latitude of several weeks in the date of the occurrence. Such attempts seem however to take in under one heading essentially separate phenomena, occasionally unlike in character and in other cases corresponding to successive stages of a process which tends to repeat itself over a given portion of the year. The result has been simply to raise doubts about the reality of the singularity phenomenon and not to provide the reliable and useful criterion for forecasters which the authors aimed at. We may notice in passing that the reality of existence of singularities is not readily susceptible to proof by statistical significance tests, since the results vary widely according to the definitions chosen (Flohn 1942).

It seems best, following Schmauss and Flohn, to define our singularities in sufficient detail to determine a broad-scale weather situation or group of situations (*Grosswetterlagen*), which can readily be seen to recur about the same date in many

* Occasionally, and mainly in the South, high or very high temperatures occur in spells of these types of weather in the British Isles n summer.

years. (See also Flohn and Hess, 1949.) These authors have in fact named various singularities in the European cycle of weather around the year, which recur in well-marked form in about 50 per cent of the years and masked in various degrees by other effects in a number of other years ; for these singularities the mean variation in date of occurrence is only about $\pm$ 3 days and the extreme variation in individual years amounts to no more than 6 to 10 days. Here we are dealing with a more closely defined entity in space and time and with a criterion which may in the end prove more informative to forecasters.

Examination of the curves obtained by plotting the long-period (20 to 60-year) mean pressures for each day of the year reveals that some of our singularities are related to the climaxes of annual trends in the surrounding geographical regions, whilst others appear to be associated with much shorter-period perturbations or oscillations superimposed upon the underlying yearly trend and appearing in like manner at many stations. We shall notice these associations in our list of singularities and trace corresponding features in the curves presented in this paper giving the annual variation of different weather types in the British Isles. All real singularities must of necessity be associated with the, as yet not fully understood, interplay of dynamic factors arising in the general circulation of the atmosphere and the thermal patterns favoured by the undersurface at different times of the year.

The singularities of our climate are therefore to be regarded as part of the course of the changing seasons. They might indeed be used to define a finer seasonal structure of the year than that given by the five broad seasons we have named, breaking down the year into more numerous " micro-seasons," seasonal phases or episodes.

Those singularities which are bound up with the main peaks of development of the zonal westerly flow of middle latitudes will be best marked in years when the westerlies are particularly prominent, and those other singularities (the majority) which are associated with other tendencies such as monsoonal effects and effects produced by concentrations of thermal gradient in high or low latitudes will be most prominent in years or seasons when the middle-latitudes westerlies are weaker than normal. It is not surprising therefore that some years are observed to be better years for singularities than others (*i.e.* showing the sequence of characteristic singularities more clearly), though fortuitous factors may still cause different degrees of development in successive singularities during the same season. With this understanding of the matter we may even learn something from the non-occurrence of particular singularities in a given year, using their development as an index of the degree of operation of some particular factor in the general circulation of the atmosphere.

We may also think of the failure of a given singularity in a given year as similar to the still more striking experience of the failure of a particular season, as for instance when the usual oceanic anticyclones of summer fail to approach the British Isles to any significant extent and the failure of this characteristic feature of the summer season gives the impression of a year without a summer. The difference in the case of a singularity which fails to show itself in a given year lies in the fact that since the time over which the tendency for such weather situations lasts is much shorter than a season (according to any of our conventional definitions of

seasons), the chance of missing any such development within the favourable period is automatically much greater. In extreme cases it may merely depend on the fortuitous element of non-arrival of suitable systems in the areas favouring their development within the right period, in other cases the developmental factors may be less favourable than usual or in opposition to more pronounced developments elsewhere (*e.g.* in the belt of westerlies).

Flohn remarks that those singularities which are marked by extensive high-pressure systems are more regular and more punctual in their occurrence than the cyclonic features which are characteristically spasmodic and subject to a random variation of date of the order of a few days. Schmauss (*loc. cit.*) found that the singularities of summer were slightly more variable in date than those of winter (mean variation 3·4 and 2·9 days respectively).

(b) *Evidence from mean figures ; features of the variation of mean pressure through the year*

Singularities which are sufficiently regular in their recurrence from year to year must be reflected by appropriate features in the trend curves obtained from daily and weekly mean values of the meteorological elements. Averages taken over longer periods, such as the conventional monthly means and running means used in presenting smoothed trend curves, must be expected to obscure the working of singularities which do not last longer than five or ten days and are commonly preceded and followed by unlike weather.

We shall therefore support the singularities we list by reference to corresponding short-term variations of the 35-year means of rainfall, sunshine, temperature, *etc.* in the different districts of the British Isles and to outstanding features of the trends of mean pressure in the surrounding regions about the dates in question.

The 35-year weekly means of rainfall, rain-days (number of days per week with over 0·2 mm rain) and sunshine are taken from the *M.O. Weekly Weather Report*, 45-51, 1929-35, and refer to the years 1881 to 1915.

For the incidence of thunder in the British Isles we have daily or weekly figures only for Edinburgh (Mossman 1896). We shall however return to a brief presentation of the trends of the monthly mean frequencies of thunder in different districts in such a way that our singularity table may be found to point easily and naturally to closer identification of the periods of the year when thunder is commonest.

The basic figures of 20 to 60-year mean pressures for each day of the year at 28 different stations in the European and Atlantic sectors of the Arctic, at the Azores and in the British Isles and Europe itself were originally worked out by Dr. Brooks, mainly for the period 1919—1938, and are available in the Meteorological Office. These results have been compared with similar work by von Elsner (1925) and Lay (1941) referring to the period 1890—1909.

Before giving our lists of singularities affecting the British Isles we must first take note of the main characteristics of the trends of mean pressure through the year shown by stations in the surrounding geographical regions.

(i) *Arctic and northern oceanic stations*, typified by Angmagsalik, Reykjavik, Lerwick and Spitsbergen, show a characteristic trend with pressure lowest around New Year or in early January and highest in May. The

May maximum is most pronounced in Greenland.

(ii) *Continental stations*, typified by Hamburg, Karlsruhe, Prague and Warsaw, show a smaller annual variation with generally lowest pressure in the warm season, though this minimum may be surpassed by individual shorter-lived fluctuations of the daily mean in winter.

(iii) *Southern oceanic and Atlantic coast stations*, represented by the Azores and less clearly by Biarritz, show a characteristic trend with highest pressure in July and lowest values reached in the season of greatest variability (unsteadiness of the annual trend curve) around February and March.

(iv) Some parts of the *British Isles and Scandinavia*, being in the transition zone between the three foregoing regions, show no noteworthy annual trend at all.

Superimposed on the annual trends there is much shorter-period variability of mean pressure, which is everywhere least marked in summer and increasingly noticeable through autumn and winter to spring. The day-to-day variability of mean pressure is greatest near the main depression track from the North Atlantic to the White Sea, least at the Azores and central European stations. It increases notably however from stations like Prague and Vienna in the heart of the continent to stations near the Baltic (even Dorpat). Some of the individual shorter-period variations can be traced at many different stations.

There are signs of a quasi-latitudinal oscillation whereby some of these shorter-period variations give simultaneously outstanding minima at the Azores and maxima at higher-latitude stations in Europe and elsewhere, *e.g.* on 23 January, 7-9 February, 15 March and 20 December.

We shall notice features of interest about the occurrence of individual shorter-period variations connected with singularities of weather in the British Isles.

(c) *The calendar of singularities*

In our list of singularities which follows we shall indicate those which are most regular and most pronounced by a system of stars, awarded as follows :—

(i) Corresponding types of weather in the British Isles (as herein defined) on the required dates in over 70 per cent of the years. (One star)

(ii) Occurrence of the corresponding *Grosswetterlagen* or specified weather phenomena at European continental stations on the specified dates in over 70 per cent of the years. (One star)

(iii) A specified, strong feature of the 35-year means for successive weeks of rainfall, rain-days (0·2 mm or more), sunshine or temperature in the British Isles (1881—1915). (One star)

(iv) The climax (highest or lowest point) of the annual trend of pressures at sea-level or of some other significant element in one of the neighbouring geographical regions. (One star)

(v) A sharp fluctuation on the curves of annual variation of pressure, with mean pressure (1890—1909) changing at a rate of 1 mb/day over 10 days or more in a specified area, (von Elsner, Lay, *loc. cit.*) (One star)

All our two- and three-star anticyclonic singularities feature in a list given by Flohn and Hess (1949) of occurrences in 67-80 per cent of the years since 1881 of typical *Grosswetterlagen* affecting central Europe on at least 3 successive days within specified calendar periods of 10-12 days. The same list quotes one other anticyclonic singularity in Europe on 28 October-6 November, which however affects the British Isles as an interval of unseasonably mild southerly weather in the middle of the late autumn rains. Fewer of the cyclonic singularities satisfy the stated conditions for inclusion in Flohn and Hess's list, but those about 25-31 December, 23-30 July (repeated in central Europe 1-10 August also) and 25 November-10 December are included, with only insignificant shifts of date and frequencies of 80-89 per cent, as well as an early phase of summer monsoon cyclonic activity affecting central Europe 9-18 June in 89 per cent of the years. It is noteworthy that the dates given for central Europe, 1-10 December, suggest that it is only the second stage of this cyclonic period in the British Isles which regularly spreads into the heart of Europe. This is the most serious discrepancy of date between the two lists.

In the following Table of singularities descriptive matter relating to the nature of the recurrent features and supporting frequency data are printed in roman type, whereas corresponding features of the *mean* values of various elements are given in *italics*. Percentage figures quoted are occurrences on any one given day in the said percentage of years examined. Weekly means for various districts of the British Isles relate to the 35-year period 1881—1915.† Buchan's and Mossman's data are for various long periods of years in the nineteenth and late eighteenth centuries (see page 423). Entries relating to Italy are recent and are taken from Flohn (1948). Notes on the annual mean pressure curves are based on von Elsner's data for 1890—1909 and Brooks's data for 1919—38.

Table of singularities affecting the British Isles

16-30 August

*** First storms of autumn

Depressions passing in high latitudes commonly produce N.'ly outbreaks in the Norwegian Sea about this time. Year's second highest frequency of W.'ly weather in the British Isles, commonly cyclonic, although an anticyclonic tendency may continue in the south. Types W and NW together about 70 per cent ; W alone 58 per cent 18 August, also exceeds 50 per cent 17-22, 24 and 26-28 August.* *One of the three wettest weeks of the year in NW. England, notable maxima of rainfall in Ireland 20-27 August and in Scotland and the rest of (especially eastern and southern) England 27 August-3 September.**

Frequency of rain-days exceeds 70 per cent in NW. Germany* on some dates, often regarded as last wave of the summer monsoon.

Minima in the mean pressure curves most clearly seen at Lerwick 20-23 August and other stations near the main Atlantic depression track — Bergen 14-22 August, Trondheim 18-22 August, Valentia 20 August, Jan Mayen 24-27 August but no obvious trace of this feature in the curves for Reykjavik or Angmagsalik, E. Greenland.

5-30 September

** Old-wives summer anticyclones

Anticyclones passing across the British Isles and Europe into Siberia. AC type about 40 per cent on peak dates 7-10 September, 16-21 September and 30 September in Britain. Cyclonic activity increases in the Mediterranean with increasing thunderiness. The dry

† Dates given for weekly normals from the *M.O. Weekly Weather Report* are the average dates of the beginning of the week and of the following week (1881-1915).

period in the Adriatic and at Rome ends about 9 September. A peak of van Bebber's Vb (inverted) depressions affecting central Europe also around 13-18 September. More cyclonic and S.'ly weather affects the British Isles after each anticyclonic system has passed away E. into the Continent. The cyclonic type recovers to 30 per cent about 24 September. In cyclonic autumns the anticyclones keep farther south and the period around 24 September is particularly liable to gales with depressions passing close to the British Isles. There is an increasing cyclonic trend during October in most years, but the frequency of anticyclones remains high in the early part of the month 1-10 October.

10-17 *September is one of the two or three driest weeks of the year in eastern and central England, notably dry in all districts. Rainfall averages fall by a half in many districts in the two weeks after 27 August-3 September.**

In parts of central Europe dry days exceed 70 per cent around 5-8 September, 17-21 September and the last days of the month, with sunshine.*

Mean pressures for European stations rise, with maxima at Valentia and Kew as early as 25-27 August. Helsingfors and Dorpat, Estonia around 29 August. Secondary maxima late in September become more prominent than this first maximum at eastern and northern stations (Reykjavik 20 September, Lerwick 26-27 September, Oslo 28-30 September and Dorpat 1 October). Meanwhile pressure remains rather steady at the Azores, but collapses at the Arctic stations in this sector in the middle of September. (The early maxima in late August show how the beginnings of this September singularity are linked with the extension of high pressure from the Azores to affect the extreme south of the British Isles during the late August stormy period. Cyclonic activity commonly continues to affect the British Isles into the first part of September.)

24 October-13 November

**** Late autumn rains

Cyclonic, often stormy, period with depressions passing close to the British Isles and into the Baltic, especially about two peak periods 26-29 October and 9-12 November. In the interval between these peaks there is a tendency to fair, mild S.'ly weather with high pressure over the continent. Year's minimum of anticyclonic weather in the British Isles 26-28 October, types other than AC 96 per cent.* Commonly one or more cyclonic centres cross the British Isles, or may even skirt the south of the country, during the first peak of cyclonic activity. The later depressions tend to pass rather further N ; and W.'ly weather in Britain increases gradually to a peak of about 50 per cent on 8-12 November. One of the year's highest peaks of E.'ly weather (20 per cent) occurs on 1-2 November, having been equalled earlier on 22 October, and falls away later. The first and most prominent autumn peak of type N occurs (18 per cent) on 25-26 October, marking a phase when N.'ly outbreaks in the Norwegian Sea are common, followed in some years by rising pressure in Scandinavia leading to the continental anticyclones common around 30 October-6 November.

*22-29 October is one of the three wettest weeks of the year in most districts of England and Ireland, but rain-days do not exceed 5 anywhere ; in parts of Scotland, especially East Scotland, the rainfall does not become outstanding till the following two weeks, when rainfall in southern districts is past its height.** (Mossman gives notable peak frequencies of rain-days in Edinburgh 30 October-6 November, about the highest of the year.)

Reversal of the seasonal cooling is shown by the mean temperature curves for most districts in Britain in the week 29 October-5 November ("St. Martin's" Summer). This is the only feature of its kind during the main autumn cooling period September-November. Cooling is resumed the following week, Buchan's cold spell of 6-12 November.*

Peaks of raininess occur in Europe, notably in Italy 23-26 October and 8-10 November, the latter dates giving the year's highest frequency of rainfall in Rome.* At Königsberg on the Baltic the frequency of rainfall also exceeds 70 per cent about 10 November.

Pressure falls to a sharp minimum first at the Atlantic stations (Valentia 23 October, Biarritz 23-25 October and Thorshavn 23-24 October). The minimum becomes less sharp and lasts longer in western and central Europe (Karlsruhe 24-28 October, Stockholm 26-30 October, Hamburg 24-30 October, Vienna 24-28 October). Meanwhile mean pressure rises at the Azores and Arctic stations with maxima at Horta, Azores 28 October, Spitsbergen 26-31 October and Angmagsalik 26-30 October.

15-24 November

*** Quiet, foggy, anticyclonic interlude

Sharp recovery of frequency of AC type in the British Isles from its late October minimum to a brief peak of 30 per cent about 17-19 November. This coincides with sharp

minima in the frequency curves of westerly and cyclonic weather. The anticyclones generally form over the British Isles and western Europe in maritime air. *Mean rainfall decreases to a minimum in all parts of Britain in the two weeks between 12 and 26 November, amounts in southern and central districts being only ½ to ⅔ of those for the previous and following weeks. Sunshine figures in Ireland and western England and Scotland higher than for the previous week, but in inland and eastern districts this is probably the foggiest period of the year.**

Subsidence conditions at the German mountain stations are more pronounced than at any other time of the year.*

*Some rise of pressure at Horta culminating on 11 November, and a vaguer maximum traceable at Valentia 12-19 November. There is a more definite peak at Kew 17-22 November, but really prominent peaks occur around these later dates in northern and north-eastern Europe (Thorshavn 16-18 November, Vardoy 17-21 November, Haparanda, Gulf of Bothnia, N. Sweden 20 November, Helsingfors 19-22 November). Mean pressure rises about 1 mb/day 15-25 November over parts of the British Isles.**

25 November-10 December

*** Early-winter storms and rains

Cyclonic period mainly associated with progressive intensification of the Atlantic westerlies, more rarely with stagnant cyclonic situations over Europe. The Atlantic westerlies approach their strongest development about the end of the year, and waves of mild air spread east until blocked and lifted by the monsoonal development of stagnant cold air in the heart of the Eurasian continent. There are two main peaks of cyclonic activity in the British Isles 25-29 November and 6-12 December and signs of a further pulse from the Atlantic around 17-20 December. Types other than AC 90 per cent ; combined frequencies of W and NW about 70 per cent, W alone reaching 50 per cent on 27 November and 50-56 per cent on 4-9 December.*

*3-10 December is on average the wettest week of the year in most districts of the British Isles**, shows some recovery in sunshine amounts for E. Scotland (lee effect) and the Channel Isles.* Mossman gives outstanding frequency of gales in Edinburgh culminating around 13 December.

There is a halt in the seasonal cooling shown by the temperature curves for 26 November-3 December and actual warming in some districts of Britain : Buchan quotes 3-9 December as a warm period.

*Pressure collapses further near the Greenland coast in mid November, e.g. at Angmagsalik 11-18 November and again around 29 November-1 December. Troughs occur at Jan Mayen and Reykjavik about two days later. The first of these troughs does not affect the European means which are rising at that time to the previously described maximum, but the second trough corresponds roughly with a pronounced feature at Lerwick and Kew 26 November and there is a further low pressure period at these stations around 3-8 December. Mean pressure falls 1 mb/day 19-29 November over the Gulf of Finland, and 0·6 mb/day over much of N. Europe as far west as the British Isles ; falls 1 to 1·2 mb/day over the N. Atlantic between Britain, Iceland and Newfoundland 24 November-4 December.**

19-23 December

** Continental and N. European anticyclones of the winter solstice

(A notable preliminary peak about 12 December commonly affects only E. and N. Europe.)

Quiet frosty weather common on the European low-lands. Year's highest peak of S.'ly weather in Britain; types AC, S and E together exceed 50 per cent. Gales still frequent in Scotland.

*Rainfall amounts (for 17-24 December) halved since two weeks earlier in southern districts.** *Noteworthy minimum in all districts, especially in the south.*

*High values of mean pressure first in peaks on the curves for stations in north-eastern and northern Europe (Helsingfors, Dorpat, Stockholm, Trondheim 9-13 December) and later in Britain and the west (Paris 16 December, Hamburg and Kew 17 December) ; also at Rome, Florence, Trieste 18-24 December. This high pressure in December and the low pressure in June seem to be the only examples of features of the mean pressure curves spreading from E. to W. ; both may be monsoonal in origin, starting in the heart of the Eurasian continent. Mean pressure rises about 1 mb/day over S. Norway and E. England 14-24 December.**

25-31 December

*** Christmastide thaw and storms of the end of the year

Cyclonic and W.'ly weather in the British Isles, carried by a second stage into central Europe. Type W reaches 50 per cent on 31 December, C 30-38 per cent on 27-29 December.

*Least sunny week of the year in Britain.** *Rainfall tending to increase but amounts not outstandingly high.* Mossman notes first peaks of snowfall in Edinburgh to reach a frequency of 15 per cent about 24 and 28 December.

Rising temperatures in Germany about 75 per cent.*

*Lowest mean pressures of the year at northern continental stations.**

5-11 January

**** Renewed storminess of early January

Year's maximum frequency of W.'ly type in Britain exceeding 50 per cent 1-11 January, 60 per cent 8 January. Types other than AC 90 per cent.*

Maximum intensity of the zonal westerlies around the hemisphere shown by many indices (Schmauss, Willett and others)*.

*The year's minimum of mean temperature curves for most districts in Britain 8-15 January, corresponding to the coldest westerlies in average and mild winters.** *Unlike the stormy periods of cyclonic W.'ly weather 25 November-10 December and earlier, rainfall amounts in this period and that of 25-31 December are not amongst the heaviest weekly figures of the year in any district.*

The mild oceanic airmasses do not penetrate into central Europe as often around these dates as with the earlier cyclonic singularities in fore-winter (peak of 46 per cent on 8 January against 51-54 per cent on 26 November, 8 December, 28 December and later 1 February).

Pressure at Horta high with a maximum on 5 January. Lowest pressures of the year at Arctic and northern oceanic stations, spread over period 2-10 January. Pressure minimum briefer and earlier (28-31 December) at continental stations and hardly noticeable at Biarritz.*

20-23 January

** Anticyclonic in Europe and southern and eastern Britain.

Dry frosty weather over the continent with sunshine on the mountains above 1,400 m, frequencies reaching 70 per cent.* Types AC, S and E together about 50 per cent in Britain.

*Sunshine averages increase sharply in E. and SE. England, but N. Scotland has second wettest week of the year 22-29 January.** *Minor maxima on rainfall curves for most western districts.*

Pressure falling at the Azores to a minimum on 23 January, rising at all northern stations to reach maxima in the British Isles around 20-23 January. Distinct maxima elsewhere in western Europe about the same dates (Paris 20-25 January), but a few days earlier at the Arctic stations (Angmagsalik and Jan Mayen 17-20 January) and a few days later in eastern Europe (Vienna 22-26 January). High pressures also occur in N. Italy around 14 January and again 20-23 January.

27 January-3 February

**** Renewed storminess, gales and rain or snow

Depressions pass into N. and central Europe from the Atlantic. The first depressions of the series commonly approach England from the SW. : situation bringing liability to freezing rain with advance of mild air after some days of frost, *cf.* 1940, 1950. Types other than AC in Britain over 80 per cent.*

*Six rain-days in the week in N. Scotland, 5 in other northern districts 29 January-5 February.** Mossman gives highest peaks of gales and rain-days (snowfall also frequent) in the whole year in Edinburgh around 29-31 January.

Precipitation frequency exceeds 70 per cent in N. Germany.*

*About the end of January and first days of February there is a distinct pressure minimum at all northern stations, first seen at Angmagsalik and Jan Mayen around 23 January, Reykjavik 24 January, reaching British stations on 31 January to 1 February, Scandinavia and central Europe 1-3 February. One cannot identify the same trough with certainty in the curves for, Spitsbergen or Bear Island, where mean pressure is low 2-12 February. On the other hand the previously mentioned Azores trough on 23 January may be connected. Pressure at Zugspitze, Bavarian Alps summit reaches year's minimum.**

8-13 February

*** February anticyclones

(A second peak follows in central and E. Europe 19-24 February.)

Year's highest frequency of winter sports conditions in Alps and S. Germany, snow over 10 cm deep in upper Bavaria 1-16 February over 80 per cent.* Record frosts in cold winters. When the anticyclones form over the British Isles in air of maritime origin, fogs are common inland. In other cases drier continental air reaches England. Combined frequencies of types AC, S and E about 50 per cent. (Italy less affected than by December and January anticyclones.)

*Setback to the seasonal warming shown by British mean temperature curves for all southern, eastern and central districts 5-12 February** : *Buchan cold spell 7-10 February.*

*Mean pressure rises again at all European stations, the peaks being earliest and least pronounced in the SW. (Biarritz 4 February, Valentia various peaks 6-18 February) ; very pronounced peaks occur in S. Scandinavia around 7-9 February and pronounced peaks reach all stations in E. Europe from Helsingfors to Vienna on 9-10 February. Mean pressure falls 1 mb/day 7-17 February in Davis Strait and rises more slowly over most of Europe.**

26 February-9 March

*** Cold, stormy period

N'ly outbreak from Norwegian Sea and cyclonic weather over North Sea and surrounding lands ; type C 30-38 per cent in Britain 26 February-2 March, peak of type N 20-22 per cent 28 February-3 March.

*One of the 5 or 6 wettest weeks of the year and highest maxima of rain-days (5 in the week in E. Scotland) except in S. Ireland and SW. England 5-12 March.** Mossman gives Edinburgh's second highest peak of gales 3 March and highest frequency of snowfall (20 per cent) around 10 March almost equalled also around 26-28 February. Accumulated snow in S. Norway normally reaches its greatest depth.

Depressions also form in the Mediterranean, causing warming in Rome and year's greatest frequency of rainfall in the Adriatic about 3-8 March.*

*The year's first notable peak of high pressure over Greenland is seen in the Angmagsalik curve 27 February. Troughs in the mean curves occur : (i) at the Azores 23 February, Valentia 24-26 February, Kew 26 February-1 March and a few days later at stations to the N. and E., also (ii) in the Barents Sea on 2 March, Haparanda 4-8 March and around the same dates in S. Scandinavia, not reaching E. Europe till about 8 March. Pressure rises about 1 mb/day over the middle Atlantic 30-35° W. 22 February-4 March and falls half as much over the North Sea and Baltic.**

12-22 March

**** Early spring anticyclones over Britain and Europe

Great diurnal range of temperature common in prevailing quiet weather in Britain and Europe. AC, N and E types in Britain together about 70 per cent.* *Sunshine increasing in all districts ; third driest week of the year in English Midlands 12-19 March.**

Dry weather in S. Germany and Austria 70 per cent.* Cold N.'ly winds in Greece and SE. Europe.

*Peaks on mean pressure curves in Britain, S. Scandinavia and Germany. Lowest mean pressure of the year at the Azores (1013 mb) 15 March.**

28 March-1 April

* Cold, stormy period

Approximate date of the first of a series of N.'ly outbreaks from the Norwegian Sea and cyclonic periods in W. and central Europe and the Mediterranean (repeated commonly about four times in April and early May), punctuated by warm, quiet anticyclonic intervals. Dates and degree of development variable (but see 12-19 April) ; cyclonic type in Britain however reaches 25-30 per cent 28 March-1 April.

Rainfall amounts increase, but reach only minor maxima in a few districts in Britain.

*Pressure at Zugspitze summit (always low with N.'ly situations) close to year's minimum.**

12-19 April

** COLD, STORMY PERIOD

The most regular of the successive stormy, cold spells in April. Year's equal-highest peak of N.'ly weather in the British Isles 28 per cent 17-19 April. Minor peak of cyclonic weather in Britain and (van Bebber's Vb depressions) in Germany and the Mediterranean. Atlantic anticyclones liable to affect W. and SW. districts of the British Isles.

Setback to seasonal increase of sunshine 9-16 *April in most districts after precocious peak in the previous week.** *Buchan cold spell* 11-14 *April.*

Mean pressure rises about 1 *mb/day* 3-13 *April in Greenland.**

29 April-16 May

**** NORTHERLY WEATHER : SOME ANTICYCLONIC INTERVALS

Equal-highest frequency of N.'ly weather in the British Isles, often anticyclonic in the west ; also leading up to year's greatest frequency of van Bebber's Vb (inverted) depressions over central Europe 17-20 May and the last spring peak of raininess in Italy 20-27 May.

Year's highest frequency of E.'ly and lowest frequency of W.'ly weather in the British Isles ; AC and E together exceed 50 per cent 29 April-3 May, AC, N and E over 70 per cent. C prominent around 7 and 17 May. Types other than W 80-90 per cent.*

Year's minimum of zonal westerlies in middle latitudes measured by various indices (Schmauss).*

7-14 May *is one of the five driest weeks of the year in S. Ireland and extreme S. England.* 14-21 *May is the sunniest week of the year in Ireland.** *Sunshine increasing in most districts, exceeds* 8 *hours a day in Channel Isles for the first time. Buchan cold spell* 9-14 *May.*

*Year's lowest pressure at Biarritz, means also low in the heart of Europe (Vienna, Prague, Warsaw). Year's highest pressure in Greenland and at other Arctic and northern oceanic stations.**

21-31 May

*** FORE-MONSOON FINE WEATHER PERIODS

Types AC and S, together about 70 per cent, give character of prevailing weather in British Isles.* Year's highest peak of type AC 46 per cent 21 May ; AC and E together over 50 per cent on 21-22, 24 and 30-31 May. *Pressure remains high over Greenland (Angmagsalik mean* 1015-20 *mb) but low over Atlantic in* 50-60° *N. : the advance of the W.'lies over the Atlantic heralds their return to Europe, preceded by an interval of warm S.'ly weather.*

Dry days in Germany and Austria 70-80 per cent about 21-22 May and 28-31 May.*

Driest week of the year in N. Ireland 21-28 *May.**

1-4 June and 12-14 June

** FIRST WAVES OF EUROPEAN SUMMER MONSOON : STORMY, COOL EPISODES

Depressions tend to move across the British Isles from the Atlantic, in one of the year's highest peaks of cyclonic weather (30-36 per cent) 1-4 June. W.'lies are still infrequent over the British Isles, but successive depressions travel rather further north and the W.'lies become more frequent ; the second monsoonal wave (" Sheep-cold ") reaches Germany around 12-14 June and the third wave 18-22 June brings the W.'lies in across the British Isles as the commonest type once more. These events are punctuated by recoveries of the anticyclonic tendency associated with advances of the Azores anticyclone.

Weekly rainfall averages show few pronounced features, perhaps because the division of the weeks confuses neighbouring cyclonic and anticyclonic periods. Mossman gives a maximum of rain-days in Edinburgh around 6 June. *The second monsoonal wave causes a setback to the seasonal warming* 11-18 *June in eastern districts of England and over much of Germany.**

Peak frequencies of thunder accompany the invasions of the continent by cool oceanic air, the year's highest frequency of thunder in S. Germany 3-5 June.*

Pressure at the Arctic stations falls erratically from the May peak before attaining steady and somewhat lower summer values ; the fall begins as early as 18 *May at Vardoy,* 27-29 *May at Spitsbergen and Angmagsalik, to reach a minimum around* 7-8 *June followed by a temporary recovery before the steady period settles in about* 25 *June. The oscillations at the stations in middle latitudes are less pronounced, though relatively clearest and earliest at the eastern stations nearest the heart of the Eurasian continent (e.g. Helsingfors and Dorpat* 4 *June, Lerwick* 7-11

June). From May onwards depressions deepen and stagnate in the heart of Eurasia and prepare the way for systems travelling into the continent from W. and NW. until the oceanic anticyclone spreads north and tends to shut off the activity.

(Baur finds that when the first monsoonal inrushes of oceanic air in early June fail and the mean temperature of the first half of the month is 2½°C or more above normal in Germany, excessive rain follows in July and August in central Europe (92 per cent) with much cyclonic activity.)

5-11 June

** June anticyclones over the British Isles and W. Europe

These anticyclones move in as extensions or offshoots of the Azores high, causing also a peak of NW.'ly weather in Britain associated with their advance. Type AC recovers to its second highest peak of the year (44 per cent) on 7 June*; AC and E together exceed 50 per cent on 5-6 June.

*4-11 June is the driest week of the year in Scotland. The period 28 May-18 June includes the sunniest weeks of the year in Scotland and most western districts.**

18-22 June and following fortnight

*** Return of the Westerlies

The most regular monsoonal invasion of the continent by cool oceanic air from W. and NW., leading to thunderiness and cyclonic activity. The south and south-west of the British Isles often remain anticyclonic. Types W, NW and AC together exceed 70 per cent*, W alone 52 per cent 20 June.

*Sharp fall in sunshine averages in all western and northern districts of British Isles ; rainfall amounts show notable maxima and are twice the averages for 4-11 June in many districts 18-25 June.** (*Buchan gives 29 June-4 July as a cold spell, perhaps the effect in Scotland of one of the waves of the European monsoon.*) *In southern and eastern districts 25 June-2 July is the sunniest week of the year (8·6 hours a day in Channel Isles) and one of the three driest weeks, with not more than 2 rain-days in some S. and E. districts including E. Scotland.*

The third wave of the monsoon reaches Germany about 24-26 June ; later waves are usually less pronounced and occur with varying regularity about 2-7 July, 18-22 July, 29 July-1 August and 16-18 August according to Flohn.

*Pressure at the Azores approaches the year's maximum.**

23-30 July and following week

** Thundery, cyclonic weather over Europe and the British Isles

Stagnant depressions common. Cyclonic type approaching its greatest frequency of the year in Britain 4-8 August accompanying peaks of the NW.'ly and W.'ly types. Type C 30-38 per cent throughout from 22 July until 8 August.

*23-30 July is the wettest week of the year in NE. England, notably wet in all districts except N. Scotland. Sunshine 20 per cent less than 25 June-2 July in southern districts, especially Channel Isles.**

Buchan's cold spell of 6-11 August seems merely to mark the onset of seasonal cooling. The year's peak of the mean temperature curve is in the week 30 July-6 August in most districts of the British Isles, almost equalled also 16-23 July ; 23-30 July is a little cooler.

Peak dates for invasion of Germany by maritime air, marked by frequent thunderstorms around 18-22 July and 29 July-1 August. Main maximum of thunderstorm-days both at Utrecht and Edinburgh (Mossman) approximately 21 July-13 August.

*Highest pressure of the year at the Azores and lowest in the continental interior, especially E. Europe.**

Note : Following this singularity late-summer anticyclones give a peak of AC type in Britain 42 per cent on 15 August. Buchan quotes 12-15 August as a warm spell, before the first storms of autumn.

(d) *Further verification and secular persistence of the singularity calendar*

Examination shows that all but one of Buchan's nine warm and cold spells (*loc. cit.* 1867) fit reasonably well into this scheme of recurrent seasonal episodes or singularities ; even the one not quoted in our table (warm spell 12-15 July)

need not be regarded as a misfit in the absence of any recognized singularity pattern about that date when the mean temperature curves are close to the peak of the year. Buchan's data referred to five stations scattered over Scotland (Orkney, Argyll, Glasgow, Edinburgh, Braemar) for the years 1857—66 and were checked in the case of Edinburgh against records covering the forty earlier years 1795—1805, 1821—1850. He claimed that all his periods show in 90 per cent or more of the years examined but found shifts of the order of 3 or 4 days in some decades.

Mossman (*loc. cit.* 1896) gives the frequency on each day of the year in Edinburgh of fog or mist, gales, hail, snow and thunder for the 50 years 1840—51 and 1857—94 and for the 125 years 1770—1894. All the main peaks of the 125-year curves and the 50-year curves agree and their correspondence with our table of singularities is easily discerned.

We have already noticed that weather entries in Pepys's Diary (1660—69) and in Boswell and Johnson's writings (1771—73) seem to show the same seasonal pattern as is seen to-day. At this point we find that even the yearly pattern of micro-seasons or singularities does not seem to have changed notably since the periods of Buchan and Mossman's data. The persistence of singularities through the centuries has been investigated by Flohn (1947), who finds only slight shifts of date amounting to no more than a few days even when singularities in the present-day weather of Greece are compared with dates given by writers of the classical period more than 2,000 years ago (Hippokrates, Demokritus and others) ; on the other hand the relative importance (amplitude, degree of development) and regularity of occurrence (percentage of years) of individual singularities has varied from century to century and sometimes from decade to decade. The material used included long records of frequency of thunder (Berlin, Stockholm, Utrecht) over more than the last 200 years and still earlier records of rainfall in Switzerland. It is interesting to note that from 28 years records between 1546 and 1576 the greatest frequency of rainfall at Zürich (over 40 per cent, in some cases 50 per cent) occurred about 5-11 January, 6-11 February, 14 and 26 April, 5 and 14 and 21 June and 26 October — all easily related to our list of present-day singularities. Rainfall also reached 40 per cent frequency about 14 March, a date which even today corresponds to a rather frequent interruption of the early spring anticyclones in central Europe by a cyclonic south-easterly situation (Vb depressions — van Bebber 1882 and 1886).

Daily or weekly figures of thunderstorm frequency in the British Isles are only available for Edinburgh* where thunder is not particularly frequent ; but from the monthly frequencies† we may nevertheless discern various regional régimes which fit in well with the finer seasonal structure of the year we have defined. Three main maxima are to be found in different regions, namely :—

(i) *Winter thunder* : A maximum in December, January and February, as at Valentia, associated with mPK and mAK airmasses in rapid motion over the warm Gulf-Stream water ; common in intensely cyclonic

* The main peaks of occurence of thunder at Edinburgh given by Mossman 1770-1894 are about 5 July, 21 July and 11 August (in each case about 6½ per cent) ; the frequency was relatively high from 19 July till 13 August, reaching 6 per cent also about 26 July. One other peak reached nearly 5½ per cent around 23 June.

† See, for instance, Marshall 1934. More up-to-date figures of the British Thunderstorm Survey are available in the Meteorological Office.

westerly situations.

(ii) *Spring, and early or late summer, southerly thunder* : Maxima in May and August-September, as at Jersey and Falmouth, associated with cyclonic situations off the west coast of Europe (in May usually after northerly outbreaks), when thunderstorms breaking out over France and Spain are brought north.

(iii) *Summer heat thunder* : A maximum in the height of summer, as at Stonyhurst and Norwich, attributable to local airmass-heating at the height of summer ; the release of thunderstorms being favoured by cold fronts and stagnant cyclonic situations in July and August. Presumably the maximum frequency accompanies the singularity about the turn of the month.

These features of the seasonal distribution of thunder in the British Isles are entirely intelligible in the light of the singularity calendar and fill in some of the implications in terms of weather of the situations listed, but without frequencies related to shorter periods than a month they cannot serve as evidence of the singularities about particular dates.

The highest daily frequencies (about 15 per cent) of the incidence of thunder at Utrecht, Holland, the nearest station to the British Isles for which daily figures are available, (taken over 205 years 1729—1940) occur as well-marked peaks of the frequency curve (Flohn 1947) about 18 July, 4 August and 23 August. Other peaks about 2 June and 24 June are only slightly less prominent (reaching 12-13 per cent against 8-10 per cent in the intervening periods, and the frequency is continuously high (12-14 per cent) between 21 July and 15 August. These dates are obviously related to the summer peaks of cyclonic type (C) in the British Isles, given in our list of singularities as stormy periods and successive waves of the European summer monsoon.

6. Conclusions

This paper has been mainly concerned with the presentation of facts. From the basic data and frequency curves of easily recognized weather types in the British Isles, we have defined a seasonal structure of the year, consisting of five broad seasons and rather over twenty shorter seasonal phases and episodes. This structure is more clearly marked in some years than others and the individual items vary in their degree of approach to the typical development in different years. At some points of the calendar alternative and quite unlike types of régime achieve stability in different years. Nevertheless the suggested division of the year seems to represent a normal pattern which can be traced through the centuries and has survived the relatively minor climatic fluctuations of historical times. The concept helps systematic study of the cycle of weather around the year and shows some obvious linkages with the state of the general circulation of the atmosphere over the northern hemisphere.

It is from this aspect that Willett (1946/47) has approached the subject, and his studies of the seasonal trends of the zonal circulation indices around the hemisphere for the seven winter seasons 1932—39 seem to supply corroborative evidence at least of certain points.

The seasonal trend of the index of zonal westerlies in 35-55° N. at sea level

shows one clear maximum in the period October to April " at the end of December or beginning of January." The trend is similar to that given by von Elsner (*loc. cit.*) for the mean pressure gradient between 30° and 60° N. in mid-Atlantic (35° W.) ; the latter is completed for the summer half-year also and shows lesser maxima about 18 June and 15 September, corresponding to maxima of the westerlies a few days later in the British Isles and Scandinavia respectively. Willett finds that the index of easterlies in 55°-70° N. has a fore-winter minimum between clear maxima in November and mid-March, fitting our two most prominent peaks of anticyclonic weather in the British Isles for the winter half year.

Willett also found that excessive values of the subtropical easterlies index (20°-35° N.) showed a significant lag correlation with high values of the middle-latitude westerlies three weeks later, though this correlation disappeared when the respective values were treated as departures from the seasonal normals. Willett interprets this as meaning that the correlation obtained was primarily due to the operation of the seasonal factor. In other words, even events on the shorter time-scale typical of individual periods of high or low zonal index or of our singularities may be an integral part of the seasonal process.

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Appendix A

Long spells (over 25 days) in British Isles 1898—1947

N.B.—Use of the qualifying adjective "predominant" indicates breaks in the spell not exceeding 3 days.

	Dates	Duration (Days)	Character
1	4 July-1 Aug. 1898	29	AC+NW
2	1 Sept.-6 Oct. 1898	36	AC+W
3	30 Nov.-5 Jan. 1898/9	35	W
4	18 Mar.-2 May 1899	46	N+NW+W
5	27 July-23 Aug. 1899	28	AC predominant
6	22 Sept.-15 Nov. 1900	55	W predominant
7	3 Dec.-2 Jan. 1900/1	31	W
8	28 April-25 May 1902	27	N+NW predominant
9	13 Oct.-13 Nov. 1902	32	W predominant
10	14 Nov.-12 Dec. 1902	29	AC+E
11	19 Feb.-4 April 1903	45	W predominant
12	28 July-31 Aug. 1903	35	W
13	20 Sept.-3 Nov. 1903	45	C
14	4 May-31 May 1905	28	AC predominant
15	22 June-21 July 1905	30	AC predominant
16	29 July-28 Aug. 1905	31	W predominant
17	29 Sept.-27 Oct. 1905	29	AC+N predominant
18	22 Nov.-18 Dec. 1905	27	W
19	17 April-21 May 1906	35	N predominant
20	1 June-13 July 1906	43	AC+N+NW+W
21	13 July-26 Aug. 1906	45	W predominant
22	2 Oct.-6 Nov. 1906	36	C+W
23	15 Nov.-17 Dec. 1906	33	W predominant
24	26 July-7 Sept. 1907	44	W predominant
25	24 Sept.-9 Nov. 1907	47	C
26	10 Nov.-23 Dec. 1907	44	W predominant
27	19 July-19 Aug. 1908	32	AC+NW predominant
28	18 Sept.-15 Nov. 1908	59	S+AC+E predominant
29	20 Jan.-16 March 1909	56	AC+N+E predominant
30	3 July-31 July 1909	29	W+NW
31	18 Dec.-18 Jan., 1909/10	32	W
32	31 Jan.-28 Feb. 1910	29	W
33	25 June-26 July 1910	32	N+AC predominant
34	27 July-30 Aug. 1910	35	C+W predominant
35	10 Feb.-12 March 1911	31	W predominant
36	16 March-13 April 1911	29	E+N+AC
37	6 May-15 June 1911	41	AC predominant
38	21 Oct.-18 Nov. 1911	29	W+C
39	15 Feb.-28 March 1912	43	S+W
40	12 April-10 May 1912	29	AC predominant
41	26 July-6 Sept. 1912	43	W+NW+C
42	7 Sept.-12 Oct. 1912	36	AC predominant
43	23 Nov.-7 Jan. 1912/3	46	W
44	24 Feb.-23 March 1913	28	W predominant
45	26 Oct.-21 Nov. 1913	26	W+C
46	24 Jan.-23 Feb. 1914	31	W+S
47	28 Feb.-26 March 1914	27	W+NW+C
48	13 May-19 June 1914	38	AC+NW+N predominant
49	19 Sept.-21 Oct. 1914	33	AC+N+E predominant
50	29 June-15 Aug. 1915	48	W+NW+C predominant
51	2 Oct.-5 Nov. 1915	35	AC+S+E predominant
52	20 Feb.-24 March 1916	33	E+N
53	8 Jan-16 Feb. 1917	40	N+E+AC
54	18 March-30 April 1917	44	N+NW predominant
55	7 Aug.-4 Sept. 1917	28	C+W
56	13 Sept.-14 Nov. 1917	63	W predominant
57	20 Nov.-13 Jan. 1917/8	55	NW predominant
58	1 March-26 March 1918	26	AC predominant
59	10 April-8 May 1918	29	E+N
60	7 Sept.-11 Oct. 1918	35	W+C
61	21 Nov.-3 Jan. 1918/9	44	W predominant
62	20 Jan.-18 Feb. 1919	30	E+AC predominant
63	23 June-7 Aug. 1919	46	N+NW predominant
64	3 Oct.-15 Nov. 1919	44	AC+E+N
65	1 Dec.-31 Dec. 1919	31	W
66	7 Jan.-4 Feb. 1920	29	W
67	5 July-9 Aug. 1920	36	W
68	10 Aug.-8 Sept. 1920	30	AC+NW
69	28 Sept.-4 Nov. 1920	38	E+AC
70	1 Jan.-31 Jan. 1921	31	W predominant
71	1 June-15 July 1921	45	AC+NW predominant
72	22 July-16 Aug. 1921	26	W+C

	Dates	Duration (Days)	Character
73	16 Sept.-30 Oct. 1921	45	AC predominant
74	5 Dec.-2 Jan. 1921/2	29	W
75	18 June-1 Aug. 1922	45	W predominant
76	6 Oct.-31 Oct. 1922	26	AC+E predominant
77	11 Nov.-11 Dec. 1922	31	AC predominant
78	12 Dec.-10 Jan. 1922/3	30	W
79	8 March-21 April 1923	45	E+S+AC
80	9 May-6 June 1923	29	N+NW
81	16 Aug.-17 Nov. 1923	93	W predominant
82	21 June-1 Sept. 1924	73	W+NW+C predominant
83	23 Nov.-5 Jan. 1924/5	45	W
84	1 March-2 April 1925	33	N+NW predominant
85	1 Nov.-26 Nov. 1926	26	W+C
86	6 Dec.-31 Dec. 1926	26	AC predominant
87	29 May-12 July 1927	45	C predominant
88	21 July-29 Aug. 1927	40	W+C
89	30 Nov.-31 Dec. 1927	32	S+E
90	4 Jan.-18 Feb. 1928	46	W
91	12 April-24 May 1928	43	E+N predominant
92	8 June-14 July 1928	37	C+W
93	5 Oct.-30 Oct. 1928	26	W predominant
94	11 Feb.-18 March 1929	36	S+E+AC
95	1 April-2 May 1929	32	E+N predominant
96	18 July-1 Sept. 1929	46	W+C predominant
97	28 Sept.-12 Nov. 1929	46	W predominant
98	24 Dec.-24 Jan. 1929/30	32	W
99	20 June-24 Aug. 1930	66	C+W+NW+N
100	4 Oct.-4 Nov. 1930	32	C
101	20 Jan.-4 March 1932	45	AC predominant
102	6 Oct.-4 Nov. 1932	30	W+C
103	13 Dec.-8 Jan. 1932/3	27	S+W
104	21 March-15 April 1933	26	AC+S+W+NW
105	7 July-1 Aug. 1933	26	W+NW predominant
106	16 Nov.-20 Dec. 1933	35	E+AC predominant
107	1 Jan.-26 Jan. 1934	26	W+S predominant
108	27 Jan.-23 Feb. 1934	28	AC+NW predominant
109	1 March-26 March 1934	26	W+C predominant
110	23 May-17 June 1934	26	AC+N+E
111	13 July-12 Aug. 1934	31	W+NW+C
112	16 Sept.-28 Oct. 1934	43	W+S+NW
113	14 Jan.-10 Feb. 1935	28	AC+NW predominant
114	4 May-1 June 1935	29	E+N predominant
115	21 July-16 Aug. 1935	27	AC+NW predominant
116	13 Sept.-11 Oct. 1935	29	W+C
117	30 June-28 July 1936	29	W+C
118	15 Sept.-11 Oct. 1936	27	AC+E predominant
119	12 Oct.-17 Nov. 1936	37	W+NW+C
120	27 Feb.-27 March 1937	29	N+E+C
121	6 Jan.-5 Feb. 1938	31	W
122	3 April-8 May 1938	36	AC+NW+N+E
123	19 June-19 July 1938	31	W+NW+C predominant
124	16 Sept.-18 Oct. 1938	33	W+C
125	17 Nov.-14 Dec. 1938	28	W+C
126	4 Feb.-8 March 1939	33	W+S predominant
127	24 April-19 May 1939	26	N+E predominant
128	28 June-12 Aug. 1939	46	W+C predominant
129	5 Nov.-11 Dec. 1939	37	W+C predominant
130	12 Dec.-17 Jan. 1939/40	37	AC predominant
131	12 March-8 April 1940	28	C
132	5 Aug.-2 Sept. 1940	29	NW predominant
133	30 Oct.-27 Nov. 1940	29	C+W
134	20 Dec.-17 Jan. 1940/41	29	AC+E+N predominant
135	4 Aug.-30 Aug. 1941	27	W+C
136	22 Oct.-16 Nov. 1941	26	AC+N+E
137	15 Feb.-12 March 1942	26	AC+E predominant
138	3 July-29 July 1942	27	W+NW predominant
139	15 Jan-15 Feb. 1943	32	W+S predominant
140	17 Feb.-14 March 1943	26	AC+NW
141	27 March-1 May 1943	36	W+NW predominant
142	5 Aug.-2 Sept. 1943	29	W+C
143	25 Dec.-16 Feb. 1943/4	54	W+NW+AC predominant
144	17 Nov.-12 Dec. 1944	26	C+W+S
145	23 Dec.-22 Jan. 1944/5	31	AC+NW+N
146	30 Jan.-1 March 1945	31	W+AC
147	13 Feb.-17 March 1946	33	AC+N+E predominant
148	25 March-24 April 1946	31	AC predominant
149	27 April-27 May 1946	41	E+N+AC predominant
150	31 May-6 July 1946	37	W predominant
151	14 July-25 Sept. 1946	74	W+C
152	29 Sept.-11 Nov. 1946	44	AC+E predominant
153	14 Nov.-12 Dec. 1946	29	C+W
154	20 Jan.-12 March 1947	52	E predominant
155	6 May-4 June 1947	29	S+AC predominant
156	14 July-3 Sept. 1947	52	AC+S+E predominant
157	22 Sept.-20 Oct. 1947	29	AC+W+NW
158	24 Dec.-21 Jan. 1947/8	29	W+C

Appendix B

Natural Seasons: British Isles 1898—1947

Season	From	Till	Duration (days)	Observed character of long spells (over 25 days)
High Summer	18 June	9 Sept.	84	Occurrence of long spells reached 48 per cent. of all years on 28 and 29 July. The year's second most prominent of max. of W, exceeding 20 per cent of years on 28-31 July. The year's second most prominent max. of C, over 11 per cent on 7-12 August. The year's only important peak of NW. Long spells of this type exceed 10 per cent on 26-29 July. A relatively lower peak of AC weather. Long spells of this type in over 5 per cent of years in middle of period (27 July-1 August and 10-16 August). Sharp fall in frequency of all above types of long spell after 16 August.
Autumn	12 Sept.	19 Nov.	71	Occurrence of long spells reaches the year's max. of 54 per cent on 6 October. W reaches a new peak, over 17 per cent, from 6 October till 12 November then falls rather steeply. The year's max. of C, reaching 12½ per cent on 1-3 November after a preliminary peak of 11 per cent on 6-11 October. Frequency high throughout middle of period. The year's max. of AC, 12½ per cent on 6 October followed by a falling trend during the remainder of October. The year's second highest peak of E, reaching 7 per cent on 6-11 October. Minor peaks of other types occurring in hybrid spells about the middle of the period.
Fore-winter	20 Nov.	19 Jan.	61	Long spells affect 40 per cent of years in a peak on 6-12 December. They drop to 32 per cent on 19-22 December during a period when shorter spells of rather different character are liable to occur, notably AC or continental E.'ly airmass weather, then regain 38 per cent on 25-31 December. The all-year max. of W. is reached about 12 December with nearly 25 per cent of years thus accounted for. The frequency of W long spells falls abruptly in first 11 days of January, and keeps on falling gradually until the spring minimum. A minor peak of AC long spells occurs on 6-14 December (6 per cent). A minor peak of E occurs 30 November -12 December (3 per cent). C types over 5 per cent on 20-21 November decline slowly till 11 December, then drop sharply to 0. NW and N show minor increases after 20 December.

Season	From	Till	Duration (days)	Observed character of long spells (over 25 days)
Late winter or *early spring*	20 Jan.	29 Mar.	70	Long spells over 30 per cent during much of period, reaching 34 per cent on 15 February and 38 per cent on 1 March. Frequency of W long spells 12½ per cent on 20 January, falling throughout to 4 per cent on 29 March ; still exceeds frequency of other individual types of long spell until 10 March, but at no date much over one-third of all long spells occurring during this season. C types of long spell begin to occur again after 26 February and reach 4½ per cent 12-26 March usually in combination with N.'ly outbreaks. The year's second most prominent max. of AC long spells, exceeding 9 per cent on 13-16 February and on 1 March, falling notably 12-19 March. The all-year max. of E, about 7½ per cent of the years examined, fell on 8-12 March, 6 per cent being exceeded from 15 February until 12 March, thereafter falling sharply. The year's max. of S, reaching 4½ per cent in hybrid spells only, mainly in combination with W on 15 February. N long spells, also mainly in hybrids, increase notably though gradually 19 February-1 March and reach a max. of 5 per cent on 18-24 March.
Spring or *early summer*	30 Mar.	17 June	80	Long spells less frequent than in any other equivalent period of the year, averaging only about 20 per cent of all years at any time in April and May and 15 per cent in early June. The year's max. of N, reaching 10 per cent on 28-30 April and falling away quickly after 19 May. A max. of AC long spells on about 8 per cent of the years on 6-8 May, with an average about 5 per cent throughout this period. A max. of E about 5 per cent is noted on 28 April-8 May, thereafter dying away during May. The all-year minimum of long W spells, reaching 0 on 4-30 May. C types occurring in no long spells from 9 April until 28 May, gradually increase at end of period.

Discussion

Mr. J. L. Galloway : No one looking through the relevant synoptic charts for the period 13 August-25 October 1949, would appreciate that, during these 74 days, temperature in London was continuously above average and that this period, in which I can detect five of Mr. Lamb's types, was exceptional for unbroken warmth in England, if indeed it has ever been surpassed. I think, therefore, that care must be taken not to associate weather too closely with pressure systems.

Likewise the period 5 April 1950, to date, which constitutes Mr. Lamb's " spring or early summer " may be considered as a single long spell of weather, in which seven short warm and six short cold spells alternated, the warm spells being, in Mr. Lamb's notation, S (3), W-E and the hybrids S-E and AC-W-E. All the warm spells, including that of 1949, were ended by a northerly, and this may be significant.

I was hoping that Mr. Lamb would have gone into the manner in which the spells began and ended, but he has not done so : perhaps he will make this question the subject of future work.

One of the difficulties in the use of Mr. Lamb's calendar of singularities will be the identification of any particular singularity at the time of occurrence. This year, for example, the average maximum temperature during the Ice Saints in London (May 11-13, Buchan's third cold spell) was over 70°F : but immediately before and after, the weather was cold : were the Ice Saints early or late ? The waves of the European monsoon were, however, easily recognisable this year, the first and second being a little early (May 28-31 and June 9-10) and the third a little late.

I was surprised to find that the total number of days in the 158 long spells was as high as 5,658, or nearly a third of the days involved. One would not have expected so great a proportion of English weather capable of a reduction to so few as seven types, nor indeed is it, for by the introduction of hybrids Mr. Lamb has in fact increased his number of types to 31, 11 of which are non-repetitive, and seven of which occur only twice in the 50 years. It is worthy of note that the W type occurs in 79 of the cases.

Scherhag, whom Mr. Lamb does not mention, has recently suggested nine typical weather situations for Europe. Of these, five are in agreement with Mr. Lamb's choice, but Scherhag replaces Mr. Lamb's E and S by a NE-E and a S-SE and adds a SW and retains van Bebber's Vb. One would have thought that classification of weather types would have been undertaken internationally, for example, by the Climatological Commission of the World Meteorological Organisation.

Airmass origin and track is of fundamental importance in the deduction of weather from pressure patterns and difficulties in the identification of these are a contributory cause of the failure of the method of analogues. My own impression is that, in Dr. Sutcliffe's words, " the atmosphere solves its differential equations in a limited number of ways and that progress in long-range forecasting should be sought not in the examination of long spells of weather *qua se*, but in the separation of pressure patterns and the study of their formation and termination." Once development in the pressure field has been decided on, weather should be fitted in with regard to the history of the air masses involved. Essentially this would take the form of an extension of Mr. Gold's work of 1919. One wonders if Mr.

Gold ever found that typical isallobaric patterns were associated with his typical pressure patterns.

Mr. E. Gold : The restriction to 7 of the number of types compared with the much larger number used 30 years ago may be justified by the difference in the object of the investigation. The larger number was necessary in an investigation aimed at providing the day-to-day forecaster with assistance in identifying previous occurrences of the type or sequence of types — on which he had to base his forecast. But a smaller number may suffice for an investigation of a more climatological character intended to bring out broad features.

The method of representing the frequency of spells may, I suggest, lead to erroneous conclusions ; it might show a maximum at an epoch when spells were ending or beginning although no spells were centred at the epoch. I suggest that it would be preferable to take the number of spells centred at the epoch.

I suggest also that a table of monthly frequency of occurrence of the different types would be a valuable supplement to the very informative curves of daily frequency.

Mr. D. J. Schove : I think that this paper has a permanent value for British meteorology and climatology. I am particularly impressed with the five natural seasons — they correspond with what I had supposed were my personal prejudices. I should be interested to know whether upper-air climatological data are available for comparison. My prejudices tell me that Mr. Lamb's " Spring " and " Autumn " correspond to periods when the prevailing winds respectively back and veer with increase of height. In his " Spring," small heat lows can form over Spain and move NNE, developing until they dominate the isobaric landscape — and actually initiate the northerly outbreak. My impression is that this does not occur before March 30 and about that date a stable W or E type is broken up by some such unexpected interruption. Likewise, in Mr. Lamb's " Autumn," depressions often unexpectedly turn SE down the North Sea. Again the westward spread of the north monsoon in mid-June often produces a week of overcast and wet weather in *e.g.* East Norfolk. From August to September the duration of anticyclones increases as insolation decreases, thus explaining the September paradox.

With regard to singularities, I have hitherto been suspicious of examples based on less than 250 day-years. Although Mr. Lamb's table is well documented for different time-ranges, I should like to ask whether a comparison with graphs for a previous long period could be made to indicate to what extent singularities are accidental. If the German claims are true, it would also be worth while to divide the fifty years into two classes in various ways to study the effect on the other singularities when one of them (say, the June monsoon) is (a) more marked than usual (b) earlier than usual. If there is evidence that other singularities are affected in harmony I think the concept would prove most useful in long-range forecasting.

Mr. L. C. W. Bonacina : Considered purely as a singularity calendar I think Mr. Lamb's representation of seasonal divisions will prove most useful. Yet I feel that his term " natural seasons " is a little unfortunate and might lead to some confusion with the ordinary conception of seasons as based on more fundamental and wider aspects of Nature. Thus it will not do to call autumnal early September,

" high summer," and omit from that category more than half of the glorious month of June when with brilliant white sunlight and intense insolation the summer comes riding in with " fierce solstitial power." Again it is impossible not to think of March as spring with all the countryside palpably beginning to respond to the return of the sun, even if there should be a few frosts and a snowstorm.

Professor MANLEY : I find myself in personal sympathy with Mr. Lamb's efforts and I should like to congratulate him on opening up a big topic for discussion. Yet I think, in the light of what Mr. Galloway has said, that what we badly need is a good calendar of British observations. If Mr. Lamb were able to list his events against say 200 years of data, we should be in a much better position. Some of the continental spells may be more feebly developed here and not really worthy of emphasis. I should not be surprised if during the Victorian spell of better Septembers to which Dr. Crowe alluded we should find that this simply meant that Mr. Lamb's anticyclonic and wetter spells were displaced by a few days earlier ; that could make for a wetter calendar month. Possibly the present climatic trend is associated with a series of such slight displacements and perhaps an emphasis on lengthening of the more favourable spells ; their effects too, would doubtless be more marked in certain districts. Accordingly I should appeal for a really long calendar of British weather. I firmly believe it could be provided since 1740 at least. Recalling as I do such things as the marked Arctic outburst late in February 1750, I feel tolerably certain that further combination of some at least of Mr. Lamb's tendencies can be provided, but first we need the data.

DR. R. S. SCORER : Should not unsettled weather in which no type persists for more than 3 days in a period of not less than 25 also be classified as a spell ?

The statistical study would be helped by putting the years in phase by measuring time from some day readily identifiable such as the end of a warm spell. Averages could then be made for a period of say 60 days before and after the chosen day over all the years in which the day can be readily identified. This would make the choice and use of analogues easier.

Captain R. B. M. LEVICK : As Mr. Lamb has pointed out, my original 50-year weather chart (presented to the Forecasting Research Division of the Meteorological Office at Dunstable) applied to the weather of the southern and eastern parts of the British Isles rather than to the north and west. Britain as a whole is somewhat too large an area to be considered all at once.

Since then I have made similar classifications of the weather of (a) Scotland and (b) Ireland. From these it appears that the *shapes* of the type-frequency diagrams (monthly) are practically identical in the three areas. The over-all average frequencies, however, differ to a certain extent. Over the 52 years 1898 — 1949 they were as follows :—

FREQUENCIES (PER CENT.) OF TYPES OF SPELLS

LOCALITY	Easterly	Northerly-Cyclonic*	Anti-cyclonic	North-Westerly	Westerly	Southerly
England	8·7	10·6	25·2	9·7	36·5	9·3
Scotland	7·7	12·5	18·5	8·6	40·5	12·2
Ireland	7·1	9·3	21·2	7·2	44·0	11·2

*—My original definition

Mr. E. J. Sumner (*communicated*) : I am mainly interested in the bearing of Mr. Lamb's work on medium-range forecasting. It seems to me that the paper contains some of the background knowledge which is essential to support existing techniques. Some of the individual types have such a high incidence on certain dates as to ensure a high degree of probability of their occurrence in any one year. However, even on occasions when the frequency is relatively low, these data can be of great practical value. If, for example, by a natural evolution from the present situation or by a judicious extrapolation of the trends which are apparent from time to time in synoptic patterns, such a type change as indicated, as is in keeping with the singularity calendar, the probability of its actually occurring *on that occasion* is greatly increased.

Modern dynamical theories and general synoptic experience both suggest the necessity in medium-range forecasting of expanding one's horizon in space and time. The extent to which even day-to-day variations in the weather are subordinate to larger-term and larger-scale processes connected with the changes of the seasons is clearly brought out in Mr. Lamb's presentation.

Mr. E. L. Hawke (*communicated*) : I should like to raise a point in connection with Mr. Lamb's finding that a peak frequency of the northerly and easterly weather types is reached in the British Isles around the beginning of May. Records show that in at least 58 of the 64 years since 1887, thunderstorms have come to Great Britain, either commonly or locally, during the first week of May. In 22 of those 58 years thunder has occurred on three or more days of that week. Fairly careful examination of the statistics has led me to believe that no other seven-day period of the year produces thundery conditions with such consistency. This high frequency of thunderstorms in early May appears to be due to one of the great annual mass-movements of the atmosphere. Sir Napier Shaw calculated that between the beginning of March and the end of May each year something like $3\frac{1}{4}$ million million tons of air are transferred from the northern hemisphere to the other side of the equator. A large proportion of this air is derived from the far northern parts of the Eurasian continent. In its lower layers it is warmed to some extent by passage over sun-heated ground, but it remains very cold up aloft when coming south-westward across Britain. Sir Napier regarded this as the explanation of those more or less regular setbacks to the advance of spring which are recognised in the weather lore of nearly all European countries — for example, the Ice Saints (11-13 May) in France, Belgium, Switzerland and Germany, and the Blackthorn Winter and the second and third of Buchan's cold periods (11-14 April and 9-14 May) in Britain. A steep lapse-rate of temperature is of course favourable to the development of thunderstorms, and it seems reasonable to suppose that the very strong tendency towards thundery weather in these islands during the first seven days of May can be attributed to the south-westward movement, in most years, of an air mass from high Eurasian latitudes at this time. Mr. Lamb's valuable study appears to support such an interpretation of the observed facts.

Mr. S. Morris Bower (*communicated*) : I do not agree with the fourth paragraph of Section 5d of Mr. Lamb's paper which states that " daily or weekly figures of thunderstorm frequency in the British Isles are only available for Edinburgh." The daily areas of overhead thunderstorms have been mapped in the Thunder-

storm Survey in England and Wales since 1925. In the early years of the Survey (Cave 1923) a calendar of the daily number of reports received was published to indicate the day-to-day changes. In 1926 (Bower) the daily number of reports received was replaced by more rigorous figures giving the daily areas of overhead storms as a percentage of the area of the country. These figures can be formed into daily or weekly groups in any way that may be required. More recently large-scale daily and period thunderstorm charts have been issued.

References

Cave, C. J. P.	1923	*Quart. J. R. Met. Soc.*, London, **49**, p. 43.
Bower, S. M.	1926	*Ibid.*, **52**, p. 405.
	1927	*Ibid.*, **53**, p. 421.
	1932	*Summer Thunderstorms*, Huddersfield, 1st Annual Report.
	1933	*Ibid.*, 2nd Annual Report.
	1934	*Ibid.*, 3rd Annual Report.
	1947	*British Thunderstorms*, Huddersfield, **2**, Pp. 112 and 128.

Mr. J. H. E. Lebon (*communicated*) : The subject of weather types, their persistence, causation and seasonal variation is of great importance in both pure and applied meteorology. Forecasters commonly realise that the tendency of the current type to persist, or, alternatively, to be replaced by another is crucial in long-period forecasting for the British Isles. The literature of the subject, however, offers but little to be read and pondered. No satisfactory classification has yet been formulated ; and few cases of type-change have been closely investigated. Compared with the number of low-pressure systems which, exhibiting peculiarities, have been dissected in the pages of the *Meteorological Magazine*, or in this journal, very few synoptic situations resulting in change of type have been scrutinised by the most acute minds engaged in synoptic meteorology. Until the atmospheric changes which precede a northward shift of the Azores high are fully understood, or we know the physical causes of persisting highs in the north Atlantic or Norwegian Sea, we shall be powerless to forecast the general character of weather during periods intermediate in length between the present forty-eight hours of normal forecasting and the season. Now that the main problems of short-period forecasting are conquered, is it not time for a sustained effort to discover the nature of spells, as the next stage towards the goal of seasonal forecasting in the westerly circulation ? It is greatly to be hoped that Mr. Lamb's investigations will be continued.

Listening to the paper when it was delivered, I wished that Mr. Lamb had devoted more time to the problem of method and classification. A frequency analysis based upon inspection of charts has been rendered respectable by distinguished workers in the past ; but apart from the difficulty of ensuring objectivity can we be sure that the different spells labelled as " westerly " over a period of years are reasonably homogeneous ? Surely there is a difference between the westerly weather of late autumn and early winter, when very deep and large lows are moving along the normal north Atlantic tracks and that of summer, when the sub-tropical high is close to our southern or south-western shores and smaller lows are brushing the north-western seaboard. During the former spells, the curvature of isobars is normally cyclonic over the whole country ; during the latter, anti-

cyclonic curvature may predominate. Would it not be possible, to avoid false classification, and eliminate subjectivity, to define spells in terms of, say, the gradient wind strength and direction at Liverpool — to select a station near the middle of the British Isles ?

Moreover, in dealing with the British Isles, where weather is so notably cyclonic, do we not fail to observe the wood because of the trees, and classify our spells primarily in terms of the direction of travel of lows ? Is it not true that successive lows are steered by the semi-persistent or persistent anticyclones of the circulation ? If we are to classify weather spells in terms of pressure-distribution and prevailing air-flow, should we not define our types with reference to the position and behaviour of the high-pressure cells ? The strength and position of the sub-tropical cells is clearly fundamental ; equally so is the behaviour of the more variable winter continental anticyclone, which may settle down over northern Europe and Scandinavia or southern Russia, and thereby refrigerate or mollify the British winter. If our weather types can thus be related to the general circulation, frequency analyses of spells can perhaps be associated with large-scale modifications of the normal or average atmospheric flow-pattern. It might thus be possible to divide the weather of a year into spells by means of a double index of wind and pressure — for the proximity of high-pressure centres to the British Isles must be correlated with mean pressure over a period. Such an index, which would be independent of subjective influences, could be correlated with the incidence of other elements over the British Isles and elsewhere in the world.

Mr. H. H. Lamb (*in reply — partly communicated*) : It is quite true that some of the types I have used could well be subdivided for certain purposes according to airmass origin, cyclonic or anticyclonic curvature of the general windstream over the country and so on. The differences between north-easterly and south-easterly weather and the cyclonic easterly type associated with van Bebber's Vb depressions are, I think, less pronounced in England than in Germany but they can still be important here. Nevertheless it was convenient for the purpose of this investigation, as Mr. Gold has suggested, to use a rather small overall number of types. Also in Germany where the 28 Gold types have been extensively used as the basis for 28 or 29 different *Grosswetterlagen*, these have been grouped into six or seven groups giving broadly similar weather in Central Europe for the purpose of exploring this seasonal structure of the year. Just as the typical character of the five broad seasons is achieved in different years in a slightly different manner, so also with the shorter seasonal phases or singularities we should expect that the broad similarity in different years will be achieved without absolute identity of type.

The warm autumn of 1949, mentioned by Mr. Galloway, was associated with a notable excess of southerly weather. The alternating sequence through spring 1950 of warm spells and cold northerly outbreaks appears from the singularity calendar to be typical of spring. There is some suggestion that all the northerly singularities are specially well developed this year. We may expect to find this sort of thing. It is well known, and has been stressed by Namias, (*Extended forecasting by mean circulation methods*, U.S.W.B. 1947), that notably similar circulation patterns tend to recur within a given low-index year and to be characteristic of that particular year.

The German workers find that years with relatively weak development of the zonal westerlies (low zonal index) tend to be good years for singularities. These are years when the monsoonal influence of patterns produced by heating and cooling of the great land-masses becomes most apparent.

Indeed we should expect that a phenomenon which is seasonal in origin would be liable to show an association with the *thermal patterns developed at each stage of the shifting seasons* and become most obvious in those years when the local thermal influences are least obscured by superimposed dynamical influences of the general circulation, in the latitudes of the prevailing westerlies.

I cannot agree with Dr. Scorer that it would be profitable to attempt to ignore the calendar and make comparisons between superficially similar pressure patterns occurring at different dates when the underlying thermal influences are quite different.

It seems to me that the singularity calendar affords a very useful guide to the *profitable use of analogues* and warns us that comparisons made with seemingly analogous situations occurring at times of the year (sometimes only a couple of weeks away), when unlike tendencies are at work, may be quite misleading.

With regard to Dr. Scorer's other suggestion, I did try to pick out the long periods of unsettled weather but found the effort profitless. There are so many different ways in which the weather can be unsettled. It may mean, for instance, that the stable cells of the atmospheric circulation are all far away from the British Isles ; or it may happen that during a given season the atmosphere fails to achieve any stable pattern of circulation over the northern hemisphere possibly because of some fundamental disharmony between the spacing of the energy sources and the strength of the circulation.

Mr. Schove agrees that the explanation of these singularities may be in the upper air, particularly I believe in the pattern of thermal winds. The thermal winds do not uniquely determine the pressure patterns observed at the earth's surface but they do mark out regions favourable for anticyclogenesis and cyclogenesis and likely paths for travelling systems. The thermal wind is most nearly represented by the actual wind about the tropopause level. It is interesting therefore that Flohn (*Naturwiss.*, **34**, p. 249, 1948) finds the amplitude of the singularity pressure wave (expressed as percentage of the mean pressure at any given level) increases with height in most cases to a maximum about the tropopause, although the 30·5 day oscillation associated with the monthly maxima of anticyclonic development affecting Germany through the winter goes on increasing in amplitude up to much greater heights.

I am inclined therefore to regard the singularity tendency (*Neigung*) for a certain type of development about given dates of the year as representing *a predisposition of the thermal pattern to favour certain developments* in certain places. In a number of cases this probably sets off a train of dynamical consequences, which may have a wave-like incidence in time through the following weeks associated with various natural time-periods required for the completion of certain processes.

Many of the singularities given in the calendar consist of *successive pulses of similar processes* : *e.g.* the Late Autumn Rains and the Early Winter Rains each contain at least two separate maxima of the zonal westerlies across the Atlantic

into Europe at roughly 10-day intervals. Where a wide range of dates is given for one singularity therefore this points to the duration of a train of events and does not imply a greater latitude in the date of incidence of any particular phase of the process. I would point out to Dr. Crowe therefore that monthly means cannot be expected to show the effects of our singularities in which the typical duration of any cyclonic or anticyclonic phase is less than 10 days, although *in some cases* we may be able to discern the effect even in the monthly figures. In general the month is too long, weekly and daily figures are needed for our purpose.

I agree with Dr. Crowe that rainfall means can be dangerous. The effects of orography are often dominant. District means were therefore used.

I agree with Mr. Bonacina that we must be careful to use the aptest names for our seasons and seasonal phases. The height of summer is in July and early August in most years. Early June is characterized by longer hours of daylight, and probably on the average by clearer air, but by generally less high temperature and weather patterns which are a sort of prelude to those of high summer.

Some further support of one point of the singularity calendar which has recently come my way seems to illustrate Mr. Sumner's remark that even the day-to-day weather process may often be subordinate to the seasonal mechanism. Of the 50 damaging tornadoes which have occurred in these islands since 1868, as many as eight were in the one week 23-29 October associated with the most reliable of all our cyclonic singularities.

Mr. Lebon has pointed our attention to the primacy of the stable anticyclones, which exercise a controlling influence on the atmospheric circulation over wide areas through the broad steering currents associated with them in the upper troposphere. This is a matter on which I am fully convinced and have myself worked on the life cycle of the individual warm anticyclonic cells, to which allusion is made in section 3 (a) of my paper. For the present purpose however time was limited and I had to make use of the material to hand ; but for the reasons set forth in section 2 I believe that Captain Levick's types — particularly when hybrid types are recognized in the longer spells — sufficiently express the position and influence of the nearest dominant high-pressure systems. Mr. Lebon's contention about the importance of the strength and position of the subtropical high-pressure cells was fully borne out by an experiment I made some years ago in forecasting rainfall over 3-day periods in S.W. Ireland, using as parameters the distance away of (1) the subsidence core of the nearest stable anticyclone and (2) the nearest depression track and its frontal envelope, as well as (3) the direction of the prevailing windstream.

Mr. Morris Bower has given us references to relevant papers arising out of the work of the *British Thunderstorm Survey*, for which I would like to thank him. However it remains true that the only daily or weekly figures of thunderstorm frequency *over long periods of years* in the British Isles so far worked up are those given by Mossman for Edinburgh. I think Mr. Schove's question about support for the singularity calendar from longer periods of years might also be answered by reference to Mossman's graphs of the frequencies of various weather elements in Edinburgh (thunder, hail, snow, gales, *etc.*) over periods of 50 and 125 years. Mossman's 125 years do not overlap with the 50 years which I have primarily

considered ; we therefore have a sort of composite record by which to check the singularity phenomena over about 175 years. It is in my opinion not difficult to interpret Mossman's curves in terms of the singularity calendar I have presented.

Finally I would like to thank Professor Manley for his suggestions for a programme of further historical research into our British weather records of the eighteenth and nineteenth centuries. Although this work was pioneered by Buchan and Mossman, whose figures appear to verify the persistence of the singularity calendar with only minor shifts of date, amounting at most to a few days, in recent years it is the German workers who have given us our main evidence for believing in the persistence of this seasonal structure. Such shifts of date as do occur in any given year or decade probably affect many successive singularities alike.

Baur, Flohn and others have found that the character of certain singularities in a particular year (notably the Christmastide thaw, the northerly outbreaks in May and the early waves of the European summer monsoon) may be very significant for the weather of the following weeks. This calendar of the seasons provides a promising framework for research in long-range forecasting and may be a valuable guide both to the short-range forecaster and the layman as well.

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The microclimate* of the potato crop

By L. BROADBENT
Rothamsted Experimental Station

(Communicated by H. L. Penman ; Manuscript received 2 February 1950, in revised form 24 June 1950)

Summary

Shade temperatures and humidities in a standard screen and at an arbitrary level of 15 cm in potato crops were continuously recorded during three summers, 1947-49.

In dry sunny periods :

(1) the maximum temperature in the crop was from 0° to 13°F higher than in the screen, and over a period of eleven weeks in 1947 averaged 6°F higher ;
(2) the crop minimum was about 2°F lower than in the screen ;
(3) over a period of five weeks in 1949 the average daily mean temperature in the crop was 2·2°F higher than in the screen, and
(4) the average daily temperature range was 8°F greater than in the screen.

Wind, wet soil and cloudy weather greatly reduced these contrasts ; occasionally the crop minimum was higher than the screen minimum.

By day, humidity was higher in the crop than in the screen, the average difference at the minima being 5 per cent in relative humidity, and 7°F in dew point. By night, the dew point in the crop was, on average, 2°F lower than in the screen, corresponding to the observed difference in mean minimum air temperatures.

During 1948 and 1949, more precise discontinuous records were taken of temperature, humidity and wind speed in and above potato crops with different densities of foliage in a variety of weather conditions. Temperature and humidity were measured at 10, 20 or 30, and 60 cm ; wind at 20, 30 and 200 cm above ground level. In the crop there was only a slight temperature gradient in the early morning and throughout cloudy days, but during sunny days gradients were produced, depending on crop density ; it was hottest at 10 cm in an open crop, at 30 cm in a dense crop ; in both it was usually coolest at 60 cm when the soil was dry, but over wet soil the lowest temperature was found at 10 cm. Except on cloudy days, temperature inversion took place before sunset whatever the foliage density or moistness of the soil.

Humidity (dew point) was usually greatest at 10 cm, but in a dense crop over dry soil water vapour transpired from the leaves often caused the air at 30 cm to be more humid than that at 10 cm.

Wind affected both temperature and humidity by increasing lapse rates and causing rapid fluctuations within the crop, particularly of humidity. Changes of wind speed within the crop took place every few seconds, the amplitude of the fluctuations depending on the speed of the wind above the crop.

1. Introduction

In the south and east of England potato stocks soon lose their cropping power because they become infected with aphid-transmitted viruses. Several species of aphid can act as vectors, but the most important is the peach-potato aphid, *Myzus persicae* (Sulzer). Regional differences in the rate at which potato virus diseases spread largely reflect the prevalence and activities of the aphids. One determining factor is the weather, which plays a large part in limiting the distribution, multiplication and movement of the insects.

Laboratory experiments on the influence of temperature on rates of development and reproduction and on factors affecting flight have been made, and numerous authors have attempted to predict or explain the consequences of weather as

* λ Strictly, *microclimate* refers to the conditions which the animal or plant experience. These are not measured by instruments placed *between* plants, and the term *ecoclimate* has been proposed as a term describing the general conditions of a habitat.

summarized in the reports of the Meteorological Office. The weather reports, however, are based on records taken in Stevenson screens at about four feet above grass, and on wind records at 10 m. Although it is obvious that conditions within and just above the crop will be different from those reported, there is little information available to indicate the extent of the difference.

Studies of crop microclimates or ecoclimates are relatively recent, the first major work on the subject being by Geiger (1927). Ramdas (1946) and his colleagues in India have been foremost in studying the microclimates of agricultural crops, but there is apparently no literature on the microclimate of the potato crop.

2. Comparison of shade temperatures in the crop and a Stevenson screen

(a) 1947

The bulbs of three mercury-in-steel thermographs and one bi-metallic thermograph were placed in small Bilham-type screens laid between the furrows of a potato crop (variety Majestic), planted 70 cm between rows and 40 cm between plants along the rows. The sensitive parts of the thermographs were about 15 cm above the soil. One screen was among dense foliage (40-50 cm high), with plants touching between the rows, one was in medium foliage (30 cm high), with plants not touching between the rows, and the other, with a bulb and a bi-metallic thermograph, was in an open crop (22 cm high), with plants not touching either in or between rows. Another bi-metallic thermograph was placed in a standard Stevenson screen over grass at the edge of the potato field.

Records were taken from 14 July to 28 September, a period of 77 days, which was dry and sunny (56 mm rainfall during the period, on 16 days). The screen temperature at maximum averaged 6°F lower than the crop temperature (Table I) ; the difference varied from 0° to 11°F. Table II gives the average sunshine and wind (at 1500 hr) on days with different maximum temperature differences. The results show that the sunnier the day, the greater was the difference between maximum temperatures ; as might be expected, the amount of sunshine in the two hours preceeding the maximum had the greatest effect. A strong wind reduced the difference between crop and screen.

There was a difference of only 0·4°F between the screen and average crop minimum temperatures in the various positions.

TABLE I. Average temperatures (°F) in crop and screen, 1947-9.

	1947 14 July – 28 Sept.		1948 30 June – 20 Sept.		1949 2 Aug. – 7 Sept.	
	max.	min.	max.	min.	max.	min.
Screen	73·0	54·5	67·0	51·8	73·3	52·5
Dense crop ..	80·6	53·8	68·2	52·4	—	—
Medium crop ..	78·3	54·2	—	—	79·6	50·5
Open crop ..	78·6	54·2	—	—	—	—
Mean in crop ..	79·0	54·1	—	—	—	—
Irrigated crop ..	—	—	—	—	75·9	50·9

TABLE II. The influence of wind and sun on temperature differences between crop* and screen, 1947 (dry period)

Crop minus screen max. temp. °F	0	1·8	3·6	5·4	7·2	9·0	10·8
No. of days	4	2	14	18	22	14	3
Mean wind (Beaufort force) at 1500 hr.	1·8	3·0	2·3	2·1	1·9	1·7	2·0
Mean sunshine per day (hr)	0·4	3·7	4·0	8·1	7·4	8·9	11·0
Mean sunshine in 2 hr period before max. temp. (hr)	0·1	1·0	0·8	1·7	1·7	1·8	1·9

Wind (Beaufort force) at 1500 hr	1	2	3	4
No. of days	30	25	14	8
Average difference between crop and screen max. temp. °F	6·5	6·1	5·6	5·4

*—Mean of 4 thermograph records.

(b) 1948

A bimetallic thermograph was again placed in a Stevenson screen over grass at the edge of the potato field and a similar instrument was placed in a small screen within the crop (variety Majestic) and was moved occasionally so that it was always in a dense, upstanding crop. Records were taken from 30 June to 20 September (83 days).

Differences between crop and screen maximum temperatures varied from —2° to 7°F. On average, the crop was 1·3°F warmer at maximum and 0·5°F warmer at minimum than the screen. The summer of 1948 was wetter and much less sunny than that of 1947 ; 129 mm of rain fell on 37 of the 82 days. As in 1947, the amount of sunshine in the two hours before maximum temperature greatly affected the difference between screen and crop temperatures, though the effect of sun was less immediately after rain. Wind reduced the difference between crop and screen more in 1948 than in 1947 because of the greater cooling produced by evaporation of water from the wetter soil of 1948 (Table III).

TABLE III.—The influence of wind and rain on temperature differences between crop and screen, 1948 (wet period)

Wind (Beaufort force) at 1500 hr.	0	1	2	3	4+
No. of days	6	41	9	16	10
Average difference between crop and screen max. temperature °F	3·6	1·6	2·0	0·5	—0·5

Day's rainfall (mm)	0	0—1·27	>1·27
No. of days	45	21	16
Average difference between crop and screen max. temperature °F	2·0	0·9	0·2

(c) 1949

The Stevenson screen was erected on the edge of the potato crop and contained the bulbs of a wet and dry mercury-in-steel thermograph. Two similar thermographs were placed in a potato crop (variety Majestic), one in a plot which was watered occasionally with an overhead rainer. These instruments had a more open scale than those used in previous years and the records were read to 0·1°F. The bulbs of the thermographs in the crop were 10 cm from the soil and were sheltered by a polished metal screening sheet : air movement was freer than in previous years when the thermographs had been inside small screens. There was no wooden floor beneath the bulbs but there was a copper water tank between them for supplying the wet bulb. Records were taken from 2 August to 7 September (37 days).

Differences between maximum temperatures in the crop and screen varied from 0·1° to 12·9°F ; differences between minimum temperatures varied from 0·8° to —5·1°F. On the average, the crop was 6·3°F warmer at the maximum and 2·0°F cooler at the minimum than the screen. The summer was dry and

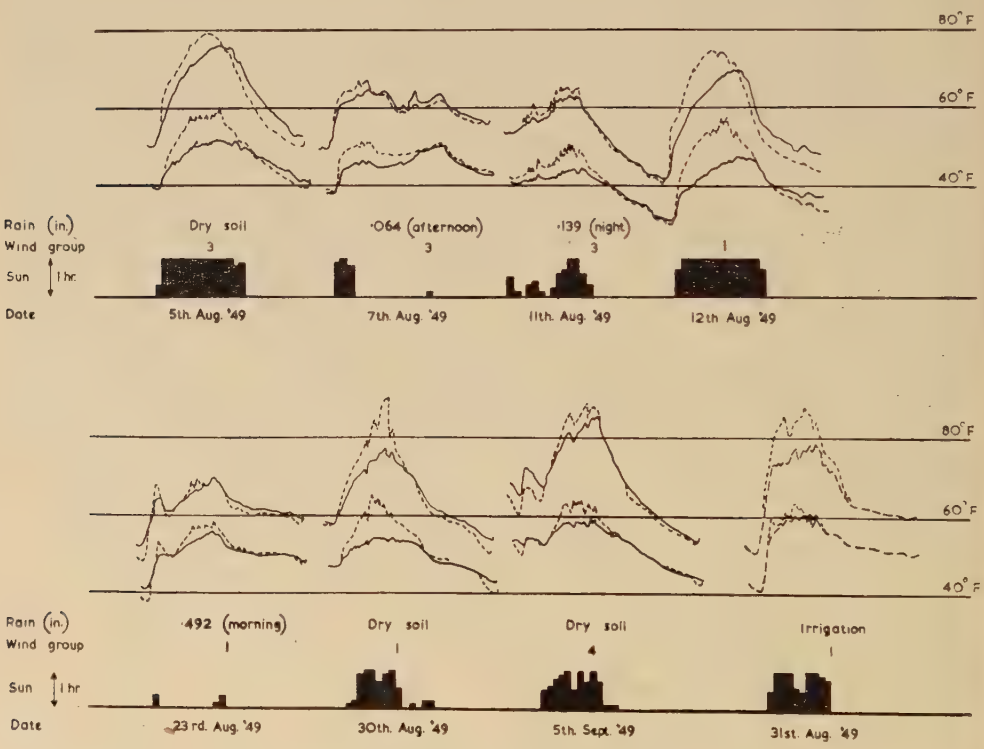


Figure 1. Wet and dry-bulb thermograph records 1949.

The wet-bulb pens were set 10°F low.
———— in Stevenson screen.
- - - - - - in potato crop.
— — — — in irrigated potato crop (31 August).

sunny and the unwatered plants grew poorly ; plants met in the rows, but scarcely between the rows. The plants in the plot which was watered occasionally grew rapidly and gave dense cover. While the instruments were in operation 27 mm of rain fell on 7 of the 37 days. The irrigated plot was watered five times, at a rate equal to about 6 mm of rain on each occasion. The influence of sunshine on temperature differences was less apparent in 1949 than in the previous years, possibly because the period was exceptionally dry and sunny and the factors which had most influence were wind and rain. As might be expected, there was less temperature difference between irrigated and non-irrigated crops on wet or windy days (Table IV).

TABLE IV.—The influence of sun, wind and rain on temperature differences between normal and irrigated crops, 1949 (dry period)

Crop minus irrigated crop max. temperature °F ..	0·2 — 6·0	6·1 — 10·0
No. of days	24	13
Mean wind (Beaufort force) at 1500 hr.	1·9	1·1
Mean rainfall (mm)	1·60	0·41
Mean sunshine in 2 hr period before max. temperature (hr)	1·4	1·5

Thermograph records, copied from the charts for eight days (Fig. 1), show the influence of sun, wind and rain on differences between screen and crop temperatures.

The results at maximum temperature are similar to those obtained in 1947 ; there is a greater difference at minimum, presumably because the thermographs in the crop had no screen floor-board insulating them from the soil.

(d) *The relation of mean temperature to the average of hourly temperatures*

The mean temperature for each day is normally obtained by taking the mean of the maximum and minimum screen temperatures. Thermograph charts for days with different types of weather have been examined and the average of 24 hourly readings compared with the means. On cloudy, wet days the mean may be considerably lower than the hourly average in the crop. A short period of sunshine in the middle of an otherwise cloudy day causes the temperature to rise and fall rapidly and the mean may be considerably higher than the hourly average. Over a period, however, the mean temperature closely approximates to the average of the hourly readings. The average difference between means in crop and screen for the 37 days in 1949 was 2·2°F ; differences varied from —1·9 to 5·6°F. It may be inferred that the mean screen temperature averages 1 to 2°F lower than the true crop mean.

(e) *Temperature range*

The variation in diurnal temperature range in the three years is given in Table V.

The average in the irrigated crop in 1949 was 24·8°F.

TABLE V.—Daily temperature range (°F) in crop and screen

Period		Crop		Screen	
		Variation	Average	Variation	Average
1947	14 July — 21 September ..	9 — 41	25	5 — 32	18
1948	30 June — 20 September ..	4 — 36	16	5 — 31	14
1949	2 August — 7 September ..	11.8 — 44.8	29.0	7·0 — 37·1	20·9

The difference in range between crop and screen varied from 0° to 14·4°F in 1947, from —3·6° to 7·2°F in 1948, and from 2·0° to 14·9°F in 1949. Increase in difference between ranges was related to increasing sunshine and decreasing wind and rain.

(f) *Discussion*

Thermographs of the types used may not be very accurate, but they will reflect the major differences that are independent of the siting of the thermographs in the crop.

When the surface soil contains a large amount of air, *i.e.* when it is dry, both its thermal capacity and thermal conductivity are small, and the effect of insolation by day is a large increase of surface temperature. By night the same considerations apply, and the soil which contains most air will cool most rapidly when the sky is clear. These principles were clearly demonstrated in 1949 when the irrigated plot, in which the spaces between the soil particles were frequently filled with water, had a higher average minimum and a lower average maximum temperature than the non-irrigated plot in which the soil was usually very dry. It should be noted that although the irrigation was applied to simulate conditions over moist soil, it also had the effect of increasing foliage density, an effect that would reduce the flow of radiation to and from the surface soil, and would change temperature extremes in the same sense as that noted. For a constant density of foliage it seems clear, however, that under wet conditions (1948 and irrigated plots of 1949) the differences between crop and screen temperatures are less extreme than under dry conditions (1947 and unirrigated plots of 1949), *i.e.* that there is no universal correction factor that can be applied to screen readings to give a measure of crop temperatures.

Soil type will also affect the daily ranges. The present records were taken over a clay-with-flints soil, normally having a high moisture content even when " dry," and it is probable that over lighter soils greater daily ranges of temperature will be experienced for the same degree of insolation and night radiation, a result found by Manley (1946) in comparing records over loam and sand.

3. Humidity

(a) 1948

A hair hygrograph was placed in a small screen within the crop near the screen containing the thermograph. No other instrument was available for use in the field, so the records could only be compared with a similar instrument in a standard screen over grass about one mile away. These instruments are notoriously unreliable, but they were carefully tested before and after use and the necessary correc-

tions were made. There was no difference recorded between screen and crop during the night. At the minimum during the day the relative humidity of the crop averaged about 5 per cent. higher than that of the screen, varying from 23 per cent higher to 6 per cent. lower.

(b) 1949

Wet and dry bulb readings were made in the screen and crop as described under 2 (c). Relative humidity and dew-point temperature have been calculated : minimum relative humidity usually coincided with maximum temperature, but both fluctuated rapidly and the average temperatures for about one hour at maximum have been taken to calculate humidity (Table VI).

TABLE VI.—Average humidity records, 1949

	Day				Night	
					Maximum humidity	
	Max. temp. °F	Dew-point °F	Relative humidity per cent.	Depression of wet bulb °F	Dew-point °F	Relative humidity per cent.
Screen ..	73	53	49	11·5	51	93
Crop ..	78	60	54	11·0	49	93
Irrigated crop	75	60	59	9·3	49	94

The relative humidity in the screen averaged 5 per cent. below that in the crop at minimum, as in 1948, and 10 per cent below that of the irrigated crop. The difference between crop and screen relative humidity varied from —9 per cent. to 19 per cent. ; between irrigated and non-irrigated crops it varied from —6 per cent. to 26 per cent. Increasing difference between crop and screen relative humidities was related to a decreasing difference in temperature and to an increase in rainfall and/or wind, whereas increasing difference between irrigated and non-irrigated crops was related to increasing difference in temperature and to a decrease in rainfall and/or wind.

Mid-day dew-point temperatures in the screen averaged 7°F lower than in the crop (Table VI). Increasing difference between crop and screen dew-points was related to decreasing temperature and rainfall and to increasing wind. The average differences in relative humidity and dew-point in crop and screen during the night were small.

The means of the maximum and minimum relative humidities were very close to the averages of the hourly readings, both in crop and screen.

The relative humidity usually decreased rapidly with increasing temperature, but the transpiration of the plants normally prevented the crop relative humidity from falling as low as that recorded in the screen. Wind increased the difference between crop and screen, causing a greater decrease in humidity above the crop than within it. The differences in dew point between crop and screen were caused by evaporation of water from the soil and plants during the day and by condensation at night. Whereas the relative humidity within the crop was much higher during the night than during the day, the warm air during the day carried more water vapour and the dew-point was higher during the day.

4. The vertical distribution of temperature and humidity within the crop

A thermistor bridge apparatus (Penman and Long 1949) was used to measure temperature and humidity at three heights with as short intervals as possible between readings ; the average time to take the six readings required for this purpose was 48 seconds. The run of the wind was measured at 2 m and at 20 cm in the crop over the same period, and from these records the probable average wind speeds at 10, 30 and 60 cm were obtained and the necessary corrections made for wet bulb readings from a wind correction curve kindly provided by Dr. Penman. The aspirated psychrometer scale of the Bilham Humidity Slide Rule was used to determine the humidity.

(a) *Temperatures in three types of potato crop, 22 July* 1949

Air temperatures were compared in three adjacent plots of potatoes (variety Majestic) which had been planted at different times. The plants were 40 cm apart, with 70 cm between rows ; other plot characteristics were :

Plot 1. Medium foliage density. Mean height of plants 45 cm ; plants touching in the row, but not across the rows ; ridged, with ridges 28 cm high.

Plot 2. Foliage density intermediate between Plots 1 and 3. Mean height of plants 37 cm ; plants not touching in the rows ; ridged as in Plot 1.

Plot 3. Open crop. Mean height of plants 29 cm ; plants not touching ; not ridged.

A light breeze during the day gave an average wind speed in the crop of 1 to 1·5 mi/hr. Cloud occasionally shaded the sun.

The soil, clay-with-flints, was very dry. Accurate wind-speed records are not available for this experiment, so dry-bulb temperatures only are considered.

Thermistors were mounted as described by Penman and Long (1949) at 10, 20 and 60 cm above the ridge, between two plants. In later experiments the middle thermistors were at 30 cm. Readings of temperature (dry bulb and wet bulb) were made as rapidly as possible from the 60 to the 10 cm levels ; they were immediately repeated in the reverse direction, thus giving two readings by each of six thermistors within a two minute period. The instrument was moved to the second plot, and then to the third, where the same procedure was repeated. The instrument was moved backwards and forwards from plot to plot in the following order : 1, 2, 3, 3, 2, 1, 1, 2, ... so that eight readings were taken in each plot on each occasion. The four readings in the first two sets and the four in the second two were each averaged to give two figures for each occasion ; although the two sets in plot 1 were separated by a wider time interval than those in plot 3, the mean time for each plot was the same. Mean times (G.M.T.) are given in the figures.

Diagrams of the vertical temperature distribution in Plots 1 and 3 (Fig. 2) show that in the early morning ($2\frac{1}{2}$ hr after sunrise) and evening, while the temperature was rising or falling rapidly, air temperatures at the three heights were

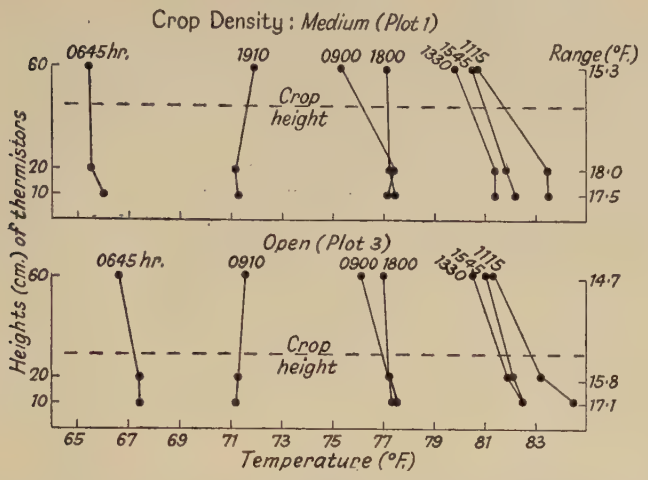


Figure 2. Vertical temperature distribution at different times during the day in potato crops of different foliage density, 22 July 1949. Each point on the graph is the average of eight readings.

similar. During the middle of the day in the 'open' crop (plot 3) there was a gradual decrease in temperature with increasing height, the air at 60 cm being 2 to 3°F cooler than at 10 cm. Among the larger plants of Plot 1 the temperature lapse was not so uniform, being greater between 20 and 60 cm than on the other plots, but small or negative between 10 and 20 cm. A period of cloud in the early afternoon reduced the temperature lapse between 10 and 60 cm to less than 2°F on all plots. At 1800 hr conditions were almost isothermal and at dusk inversion had occurred, the ground being cooler than the air above.

Included in Fig. 2 are the ranges between the extreme temperatures measured during the day. These increased with increasing density of foliage. In the open crop (Plot 1) and intermediate (Plot 2) the biggest range was at 10 cm, whereas among the denser foliage of Plot 3 it was at 20 cm.

(b) *Temperature and humidity in dense and medium crops, dry and irrigated, 28 July 1949*

This experiment compared conditions at heights of 10, 30 and 60 cm in four plots of Majestic potatoes. The plants were 45 cm apart, the rows 65 cm.

Plot 1.	*Medium, dry.*	Plants touching in the row, but only occasionally between the rows ; somewhat sprawling ; mean height 55 cm.
Plot 2.	*Dense, dry.*	Previously watered twice weekly, but not for six days before the experiment ; soil dry. Plants touching both in the row and between rows ; mean height 60 cm.
Plot 3.	*Medium, wet.*	As Plot 1, but irrigated for the experiment. Mean height 50 cm.
Plot 4.	*Dense, wet.*	As Plot 2, but irrigated for the experiment. Mean height 65 cm.

To simulate conditions after rain, the 'wet' plots were irrigated with an overhead rainer for 7 min immediately before the readings were taken ; the rate of watering was equivalent to about 13 mm of rain per hour, thus both the ground and foliage were wet. Before the last four groups of readings irrigation lasted 4 min only, as the ground was then thoroughly wet.

Nine groups of readings were taken, with two sets of double readings per thermistor in each group. The instrument was moved from plot to plot in the following order : 2, 1, 4, 3, 3, 4, 1, 2. Cup anemometers (Sheppard type) were operated at 2 m and at 20 cm from the soil between two rows in Plot 1. Wind at 2 m varied from 4 to 7 mi/hr, at 20 cm from 0·7 to 1·6 mi/hr.

0610 — 0645 hr. The temperature of the upper air among the plants was rising, but the direct rays of the sun did not reach the soil. In all plots the air at 10 cm was coolest (Fig. 3). The warmest air was at 30 cm in the medium dry plot, at 60 cm in the dense dry plot.

0910 — 1015 hr. The sun reached the soil in the medium dry plot, causing the air at 10 cm to be about 3°F warmer than at 60 cm. The foliage in the dense dry plot prevented the insolation of the soil and the air at 30 cm was the warmest.

1320 — 1445 hr. With light cloud cover the middle of the medium dry plot became warmest, and the middle or upper air of the dense dry plot remained warmer than the lower air.

1715 hr. Temperature inversion had formed.

Temperature gradients over wet soil were opposite to those over dry, the lower air being coolest throughout the day (except at 0910 hr in the medium wet

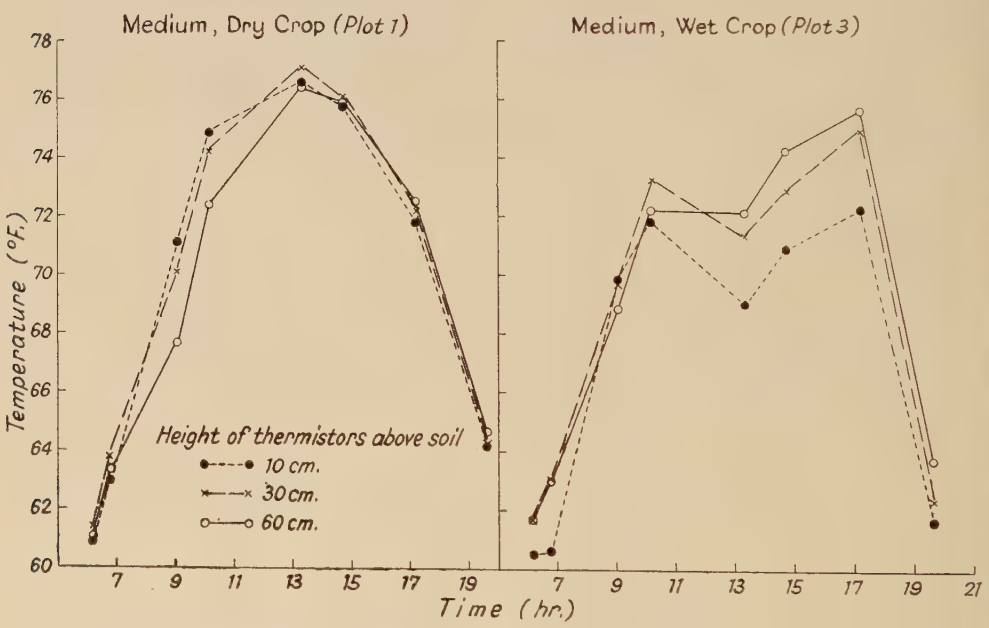
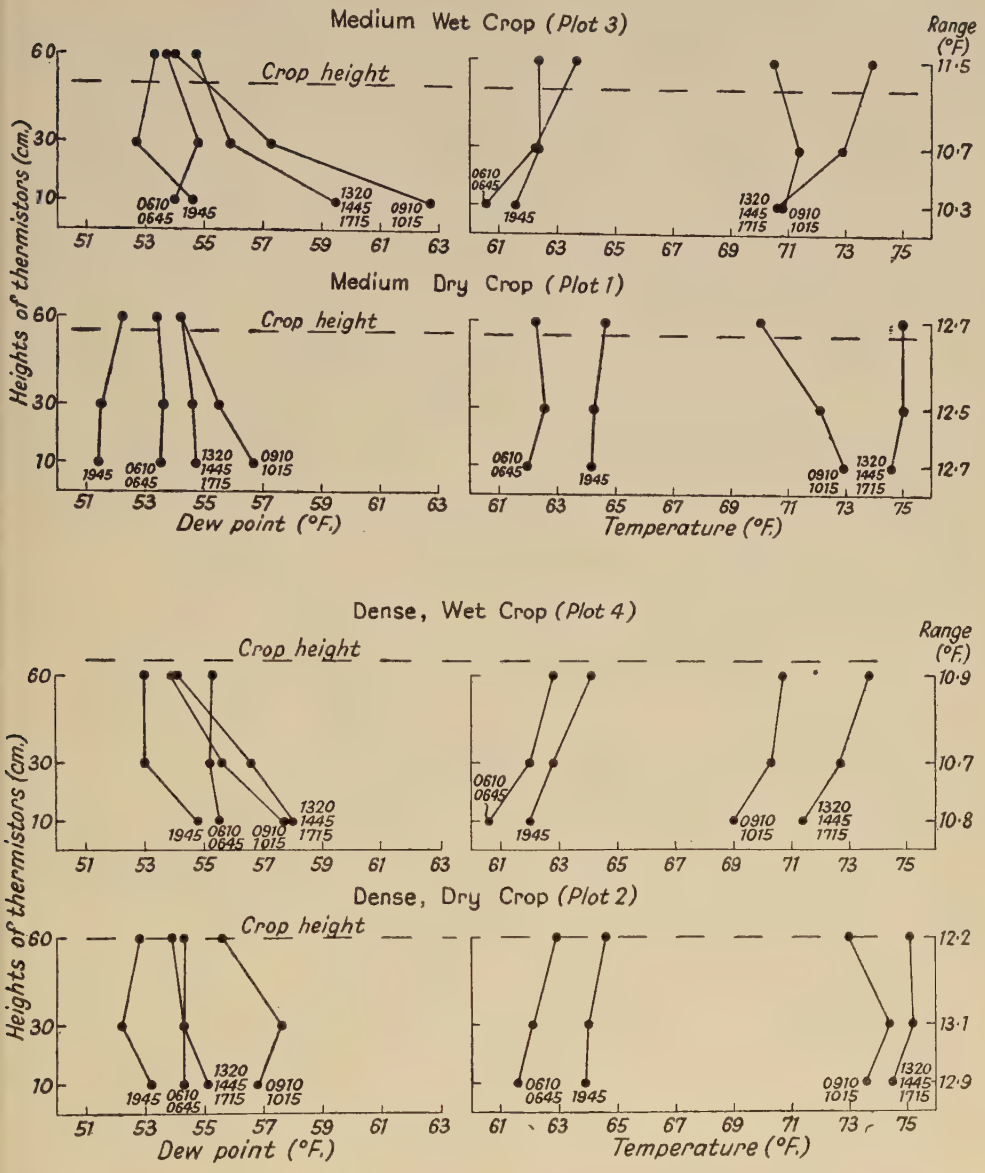


Figure 3. Temperatures at three heights in wet and dry potato crops of medium foilage density, 28 July 1949. Each point on the graph is the average of four readings. Sunrise 0416 hr ; sunset 1956 hr.



Figures 4a, 4b. Vertical distribution of dew-point and air temperatures at three heights in wet and dry potato crops of (a) dense and (b) medium foliage, 28 July 1949.

crop). In the medium wet crop the air at 60 cm was over 3°F warmer than at 10 cm from 1320 to 1715 hr.

Figs. 4a, 4b show air temperatures at three heights. When the vertical temperature distribution was similar at different times of recording, these have been pooled to simplify the diagrams. Range between the extreme temperatures measured was greatest at 30 cm in the dense dry crop over dry soil, least at 10 cm

in the medium crop over wet soil, presumably because much of the insolation was used up as latent heat of evaporation in the wet plots. The range tended to decrease with increasing height over dry soil, but to decrease with decreasing height over wet soil.

The humidity records are presented as dew-point temperatures in Figs. 4a, 4b. In all plots the air at 60 cm was the driest, except in the evening, when the air at 30 cm was sometimes drier. Over dry soil there was little difference between the dew-points at 10 and 30 cm but over the wet soil, the air at 10 cm was much moister than at 30 cm. In the early morning there was little difference in dew-point between the three heights. The dew-point first increased to a maximum about 1000 hr and then fell during the rest of the day to reach a minimum at dusk. Two factors probably influenced the extent of daily fluctuation in the moisture content of the air ; (1) the amount of evaporation of water from the soil and (2) the amount of water vapour lost by the plants. Where the sun's rays reached the soil, as in the medium crops, the water evaporated from the soil played a dominant part and the air at 10 cm was the most moist. Where dense foliage prevented the sunshine from reaching the dry soil in Plot 2, transpiration was the dominant factor and the air at 30 cm had the highest dew-point.

(c) *Temperature and humidity at three heights in a dense potato crop*

(i) 5 August 1949

In the previous experiments the movement of the instrument from plot to plot disturbed the plants and it was impracticable to place the instrument in the same position in each plot on every occasion. In the present experiment the instrument was set up in a crop of potatoes (variety King Edward) and left in position while 4 groups of readings were taken, each consisting of ten sets of double readings. The plants averaged 60 cm in height, forming a dense crop. Wind records were taken as in the previous experiment ; at 2 m the wind varied from 7 to 9 mi/hr, at 20 cm from 1·2 to 1·4 mi/hr. There was bright sunshine during the experiment ; the soil was dry.

The thermistor at 30 cm recorded the highest temperature throughout the experiment, showing that the middle was the warmest part of the crop. Both temperature and dew-point were negatively correlated with wind speed, and, as might be expected, the wind had least effect at the base of the plants. Diagrams of vertical temperature distribution (Fig. 5), giving the averages for each of the four periods, show clearly the trends of temperature and dew-point in the crop. During the third period when the sun almost reached the base of the plants, the temperature at 30 cm was about 4°F higher than that at 60 cm, but there was little difference between temperatures at 30 and 10 cm. At the same time transpiration was at its maximum and the dew-point gradients were steepest, the dew-point at 30 cm being 4·6°F higher than at 60 cm and 2·1°F higher than at 10 cm.

(ii) 12 August 1949

The day was fine and almost cloudless, with light breezes, averaging 3 mi/hr at 2 m ; 0·5 to 0·7 mi/hr at 20 cm. The thermistors were in similar positions in the same crop as on 5 August.

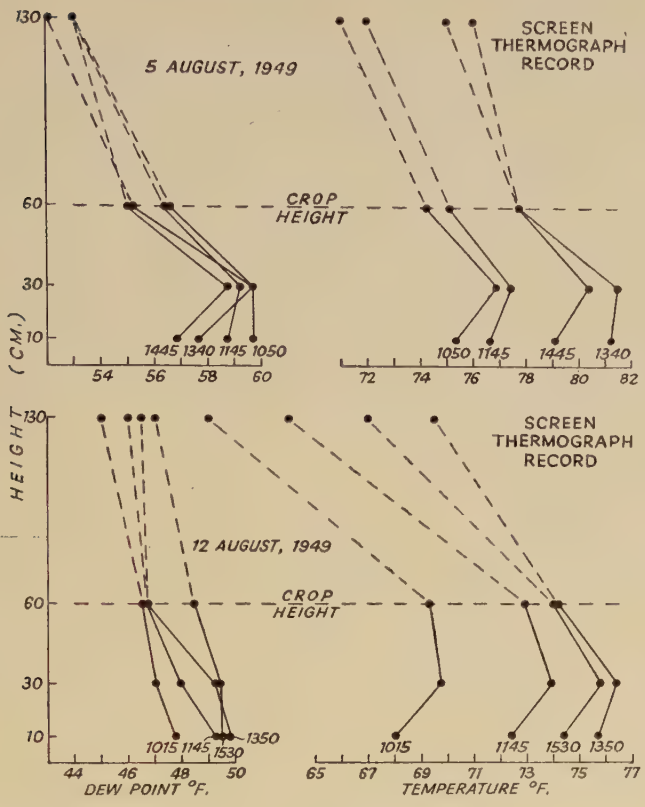


Figure 5. Vertical distribution of dew-point and air temperatures in a potato crop, 5 and 12 August 1949. Each point on the diagram at the three lower levels is the average of twenty readings.

The middle of the crop was again the warmest region (Figs. 5, 6) after the first few minutes of the first period. At 1350 hr (about maximum temperature, Fig. 5) there was a bigger difference between 30 and 60 cm (2·3°F) than between 30 and 10 cm (0·7°F).

Fig. 6 shows very clearly the effect of wind on temperature and humidity. A short period of wind over 5 mi/hr at 2 m in period 3 (1350 hr) produced no effect at 10 cm, caused a small drop in temperature at 30 cm and an appreciable drop at 60 cm. When the wind speed was low the dew-point temperature rose, but an increase in wind dispersed the accumulated water vapour and the dew-point fell. Fluctuations in dew-point were much larger and more frequent than fluctuations in air temperature. As there was less air disturbance near the base of the crop, the hydrolapse was greater in higher winds. This is illustrated in Fig. 5 ; 5 August was windy whereas 12 August was calmer, and the variation of dew point with height was much greater on the 5th than on the 12th. On 5 August the air at 30 cm was more moist than at 10 cm whereas on 12 August the humidity near the ground was higher than at 30 cm, presumably because there was rain on 11 August and the soil was still wet. In the calmer conditions of 12 August, warm

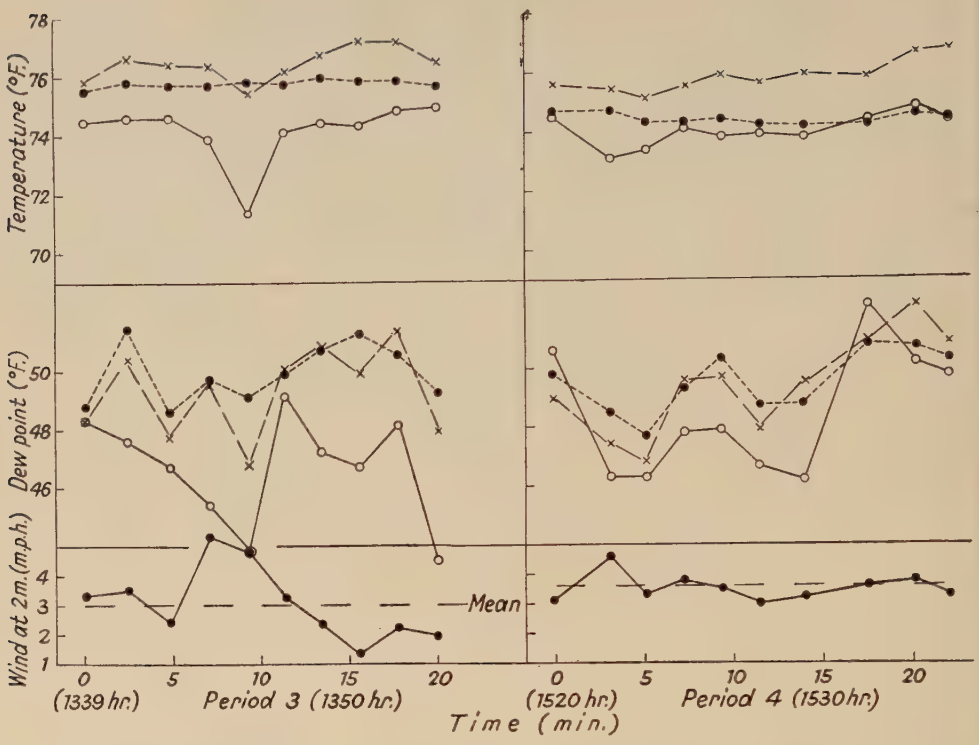


Figure 6. Air and dew-point temperatures at three heights in a potato crop, and wind speed at 2 m above the soil in the crop, 12 August 1949. Each point on the graph is the average of two readings. (For Key see Fig. 3).

air accumulated among the plants and there was a bigger difference between crop and screen temperatures than on the windy 5 August (Fig. 5).

5. Wind speed within the crop

The wind speed within potato crops of different densities and the speeds at heights of 2 m and 10 m above the soil have previously been compared (Broadbent 1948). The cup anemometer records then obtained at 2 m and 20 cm are shown in Fig. 7, together with the results obtained in 1949. The regression lines for 1949 are similar to those for crops of comparable density in 1947, and show that the average wind speed in the crop rarely exceeds 3 mi/hr, even when there is an average wind of 15 mi/hr at 2 m.

To obtain an estimate of the type of fluctuations within the crop which make up the run recorded by the cup anemometer, the thermistor anemometer (Penman and Long 1949) was operated in a dense crop of the variety King Edward, 60 cm high. Readings at a height of 30 cm were taken every five seconds and the cup anemometers were operated in the crop at 20 cm and at 2 m (Fig. 8). When the wind speed at 2 m averaged 8 mi/hr, the fluctuations in the crop were greater than when the wind at 2 m averaged 3 mi/hr but fluctuations were frequent on both days.

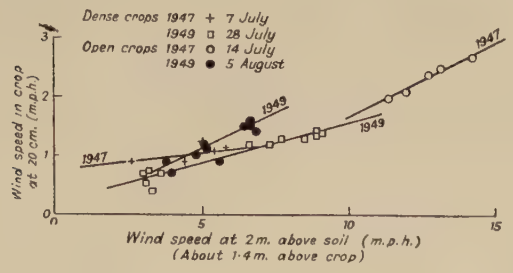


Figure 7. Regression lines showing the correlation of wind speeds at 2 m and at 20 cm above the soil in dense and open potato crops.

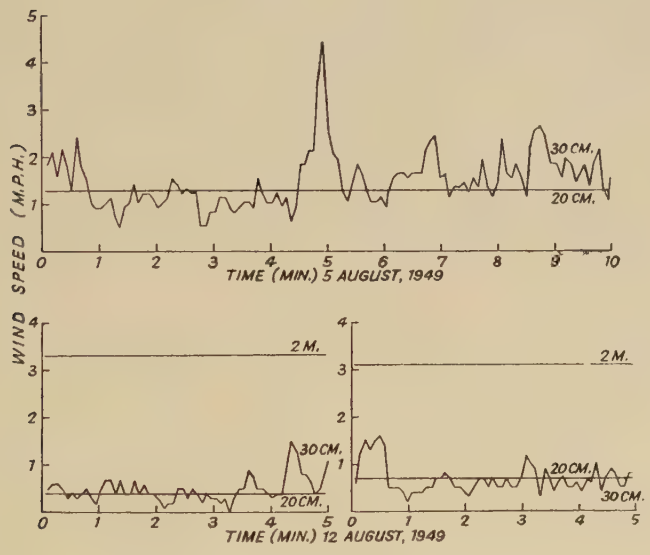


Figure 8. Wind speed records with cup anemometers at 20 cm and 2 m above the soil in a potato crop with dense foliage 60 cm high, and the thermistor anemometer records taken at 30 cm every 5 sec, 5 and 12 August 1949. (Average wind speed at 2 m on 5 August was 7·7 mi/hr).

6. Discussion

The experiments have given quantitative measures of effects that were anticipated on theoretical grounds. The general daily trend of temperature within a crop must depend on (i) the supply of incoming radiation and the level at which it is intercepted ; (ii) the rate of loss of long-wave radiation ; (iii) the extent to which the balance between (i) and (ii) is used up in evaporation either from the soil or the plants, so bringing in considerations of level again ; and (iv) the extent to which turbulent transport of heat to or from the crop is possible. Similarly, the daily trend of humidity in the crop is determined by the same general principles, with the necessary modifications introduced by the need for a supply of evaporable water to increase absolute humidity and the limitation set on relative humidity by the possibility of reaching saturation point in the air.

So it is found that over dry soil on a sunny day the lower air of a crop becomes progressively warmer than the upper air during the morning ; the trend is reversed during the afternoon and inversion occurs before sunset. From the thermograph records, already discussed (section 2f), it can be inferred that the inversion in the crop would persist throughout clear nights. In cloudy weather conditions tend to be isothermal during day and night. When evaporation can take place at the level intercepting insolation, temperatures tend to be lower and humidities higher at that level, *e.g.* near ground level over wet soil or among the leaves where plants intermingle to form a dense cover. The gradients of temperature and humidity are necessarily influenced by turbulent mixing, and the wind records show how little the effect of external air movement penetrates the plant cover. The effect of the crop is to impose a steeply falling gradient of turbulence from the top of the crop downwards, so that the lapse rates of temperature and humidity that are produced in near-calm conditions are increased appreciably in windy conditions of equivalent insolation. The penetration of eddies into the crop produces fluctuations in temperature ; these are greater in the wet-bulb than the dry-bulb temperatures. Part of this difference in effect may arise from a different time constant for the wet-bulb thermometer, but the effect may be real in that eddies will disperse pockets of vapour that accumulate and are trapped among the plants.

The experiments on lapse rates have been limited to daylight hours but the results conform to the general diurnal cycle found by Baum (1949) working over wheat stubble.

These results apply only to the air between plants, but they approximate closer than Stevenson screen records to conditions in the layer of air in contact with the leaf or surrounding the animal or pathogen on the leaf. Temperatures near the leaf surface will be more extreme than those measured at a distance of a few centimetres, for the plant will absorb heat during the day and thus be warmer than the surrounding air ; it will radiate heat at night and then be cooler than the ambient air. It is almost certain that the air near the leaf surface will be more humid at all times than that a short distance away.

Acknowledgments

The co-operation of Dr. H. L. Penman, Mr. I. Long and Mr. M. J. T. Norman is gratefully acknowledged. In addition to designing the apparatus Dr. Penman has given much advice and criticism. Mr. Norman recorded during the experiments and helped to compile the data. The " mercury-in-steel " thermographs were kindly lent by the Meteorological Office.

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DISCUSSION

Thunderstorms in Great Britain

The May 1950 meeting of the Society took the form of a discussion on Thunderstorms in Great Britain, Mr. L. C. W. Bonacina, Vice-President, being in the chair.

The openers of the discussion were Dr. J. S. Forrest, who read his paper "Variations in thunderstorm severity in Great Britain" (p. 277 of this volume) and Mr. S. Morris Bower, who gave an account (following) of recent work of the British Thunderstorm Census Organisation.

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Recent work of the Thunderstorm Census Organisation

By S. MORRIS BOWER
Director, Thunderstorm Census Organisation

(Manuscript received 29 June 1950, in revised form 7 August 1950)

Summary

The weakness of the definition of a day with a thunderstorm as any civil day on which thunder is *heard* at a station, and the great difficulty of interpreting data on such a basis, is illustrated. An example of a thunderstorm chart based on the daily areas of *overhead* thunderstorms drawn from a close network of recording stations is presented and is compared with the "thunder-heard" results. A method of producing detailed period and average maps, published as *County Thunderstorm Surveys*, is shown. The similar charting of daily areas of lightning damage provides a convenient and reliable method of examining the distribution of storm severity, and has many practical applications.

Analyses of thunderstorms on individual days by means of hourly isochrones, published as *Daily Thunderstorm Charts*, present new opportunities for detailed comparison with rainfall maps and with radio thunderstorm recordings.

1. Historical introduction

Various surveys of thunderstorms (Symons 1858, *et seq.* ; Marriott 1888, *et seq.* ; Mossman 1897 ; Fairgrieve 1912 ; Cave 1912, *et seq.*, and others) have been undertaken in the last hundred years and the accumulated evidence of these is gradually being brought together. The present *Thunderstorm Census Organisation* dates from 1924, and derives its evidence from a close network of observers, professional and voluntary, well distributed over the British Isles, with the assistance of information supplied by the Meteorological Office.

The daily areas of *overhead* thunderstorms have been plotted and measured over twenty-five years in the present Survey, and have produced a great wealth of detail in both map and statistical form. More recently, the daily areas of damage by lightning have also been charted and the ratio between the damage area and the corresponding overhead area appears to give an excellent measure of storm severity.

On the climatological side, analysis of the daily charts by means of hourly isochrones has made direct comparison with rainfall maps possible. The lines of intersection of the isochrones (Bower 1947a) can be specially studied in connection with the well-known belts of heavy thunderstorm rainfall.

2. Definition of a thunderstorm

The definition of a " day with a thunderstorm " at a station, as any civil day on which thunder is *heard*, is convenient, but subject to a great deal of ambiguity and observational error. The thunderstorm charts show that, in spells of weather, thunderstorm areas of moderate size frequently occur close together on almost consecutive dates but may not overlap. When, however, a marginal band of, say, ten miles in width is added to represent the area over which thunder may be heard, it often happens that two or three such areas overlap. It is then easy to see that a composite period map (Bower 1950b) can show two or three " days with thunderstorms " at a place where no overhead thunderstorm has occurred.

A reasonable size for an overhead storm area on a particular day in this country may be taken as a thousand square miles. If this area is supposed to be roughly circular and an outer margin ten miles in width be added to represent the area over which thunder may be heard, we see that a very vigilant station would be likely to record a day with thunder heard about two-and-a-half times as frequently as a day with an overhead thunderstorm.

Further errors are introduced by the varying personal factors of the observers, by the method by which the twenty-four hours are covered, by wind direction and by variations in the immediate surroundings of the recorders who may also be expected occasionally to be badly placed to hear thunder. Moreover it is obviously quite out of the question to maintain a night-and-day watch at a single-observer station, of which there are many. Lack of vigilance produces errors which are very ambiguous and almost all deficiencies, and many stations must, therefore, greatly underestimate their days with thunder heard.

It is useful to plot (Fig. 1) the data for the average annual number of days with thunder heard (taken as days with thunderstorms) over an area, as given in the *Monthly Weather Report* of the Meteorological Office. It is at once seen that stations in close proximity give an alarmingly wide variation in average, and it is hard to find any trustworthy method of interpreting the data and of drawing up any reliable distribution map at all.

Fig. 2 shows the summations of the daily *overhead* thunderstorm areas (Bower 1948b) for the same period of years, but for another district, expressed as annual averages. The averages are seen to be in good harmony with one another, and the overhead thunderstorm map presents a great wealth of detail which it seems quite impossible to obtain from the thunder-heard plottings. Comparison of the data also shows that the frequency of days with thunder heard rises to a maximum value of about two-and-a-half times the days with overhead thunderstorms at a minority of stations. Considering Fig. 1 alone, the high figures from this minority of stations might easily be felt to be quite out of harmony with the majority, be doubted in consequence, and lead to a disastrous interpretation of the data.

Figure 1. Average annual number of days with thunder heard (Yorkshire W.R.)
* Manchester = Whitworth Park + Oldham Road.
(N.B. The figures are plotted in the positions of the observing stations.)

The action of wind in making thunder more easily audible downwind than in other directions must also be considered. The point may be illustrated by comparing the annual map (Bower 1949) of overhead thunderstorms in England and Wales in 1949 (Fig. 3) with a similar map for the same period, prepared by the Electrical Research Association (Golde 1950), which includes thunder-heard data. It will be noticed that the maxima of " thunder-heard " thunderstorms tend to occur to the north-east, or generally down-wind, from the maxima of overhead thunderstorms, and that the effect of wind on the statistics can be both cumulative and great.

Summing up the evidence, it appears to be essential to replace the "day with thunder heard" definition by one of a " day with overhead thunderstorm " before any detailed storm charts can be drawn up. At the same time the change to the day with an overhead storm presents a much more ideal subject for observation. An overhead storm has been found to be capable of record with excellent precision, both visually and aurally, by a great many people.

3. Thunderstorm plotting

The thunderstorm record card has been specially designed to facilitate the collection of data. Each record is scrutinized individually, and rejected if proper confirmatory evidence is lacking. The data are indexed both chronologically and

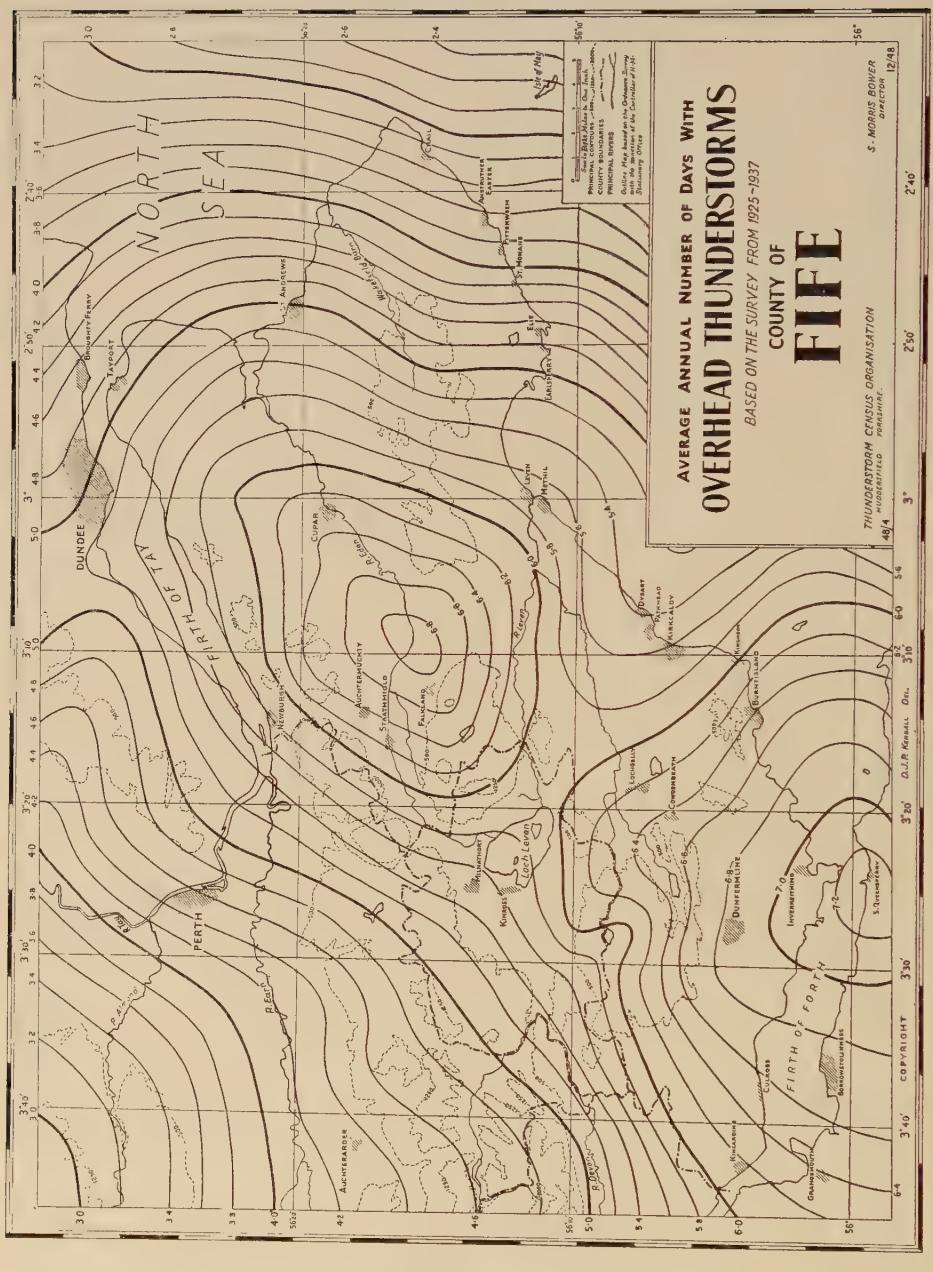

Figure 2. County Thunderstorm Survey — Fifeshire.

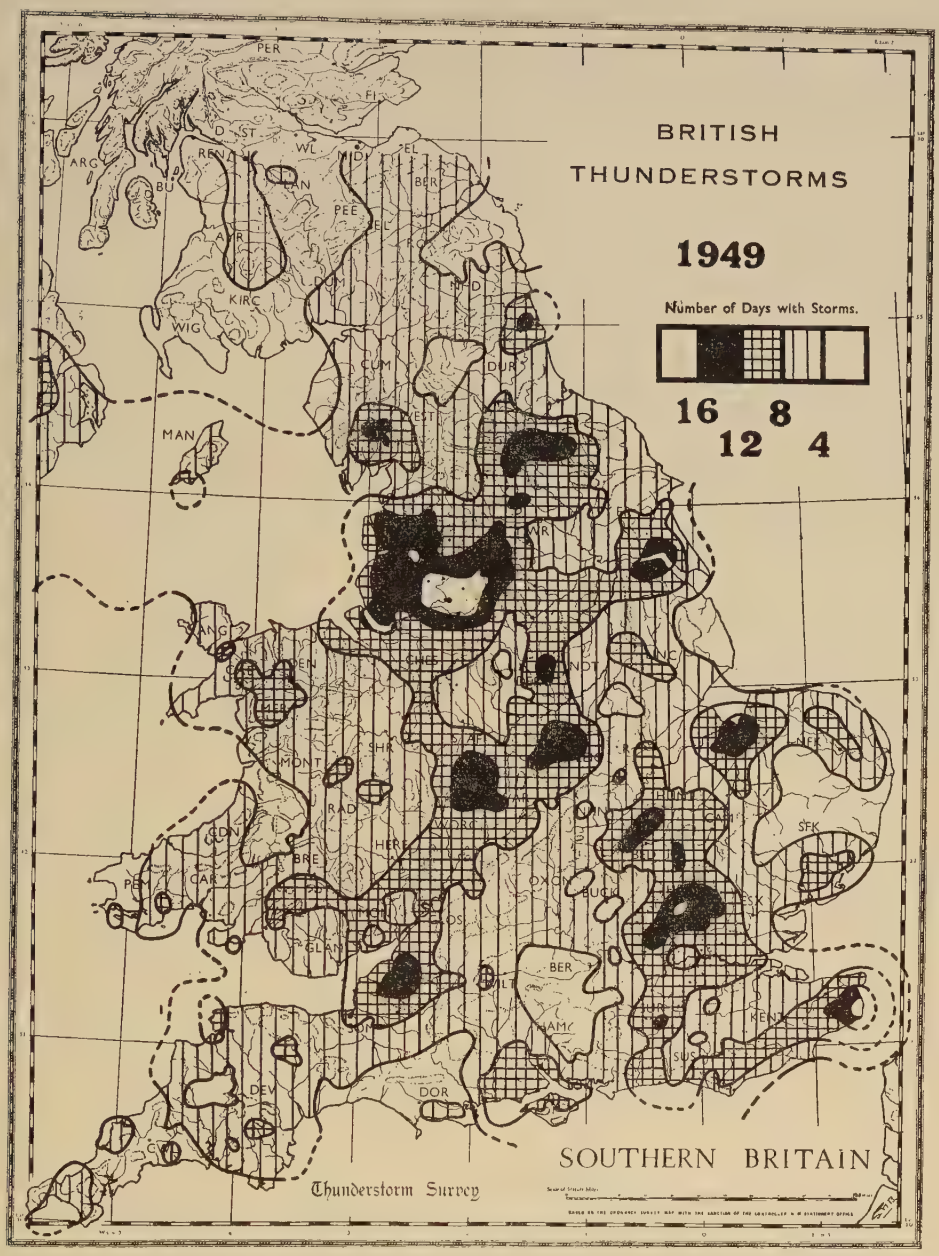

Figure 3. Distribution of days with overhead thunderstorms in England and Wales in 1949. (Based on Research Publication 49/12)

geographically, so that evidence may conveniently be made available in various forms. A separate index of items of damage has been maintained since 1935, and the survey of trees struck by lightning was organised as a separate section by the late Mr. S. T. E. Dark, some eighteen years ago ; this section is now being continued by the Exeter University Field Club.

The original observations are plotted and grouped, and distant storms are triangulated between pairs of stations and between groups (Bower 1934). The grouping of the records prevents the responsibility for continuous observation devolving on the individual observer, and, consequently, no attempt is made to derive period charts from aggregate records from particular stations. The method automatically protects the observer ; if he reports something which is not thunder, his record is eliminated through lack of confirmation, while if he misses a thunderstorm which actually occurs, his neighbours supply the missing data for him. Observers' records are supplemented by numerous Press reports, and also by radio recordings (Sferics) supplied by courtesy of the Director, Meteorological Office.

About a hundred plotting symbols are used covering the main activities connected with thunderstorms and the objects most frequently struck by lightning. Some of the symbols are common to the Ordnance Survey. The original maps, of which a sample section is reproduced in Fig. 4, are drawn out for the whole of the British Isles on the scale of ten miles to the inch. It will be seen that if the network of stations is maintained close to the observational saturation level it is easy to delineate the daily areas of overhead thunderstorms and of damage by lightning to a considerable degree of accuracy. Much of the lightning damage in country districts is accounted for by such items as trees, cows, stacks and barns ; in town areas the story is continued in terms of chimneys, roofs and electrical failures. With the principal exception of transformer damage, the bulk of the damage evidence indicates strokes to earth on the spot.

It will be noticed that the grouping of the records, and the delineation of the *areas* to form the basic material of the Survey, cut out many of the complications, so frequently encountered, arising from the distribution of population and its changes. Obviously some districts provide more records than others, and some basic daily areas are drawn on the evidence of many more observers per thousand square miles than others. So long, however, as the observations in the weakest part of the network of recorders are up to saturation level — which can be determined experimentally — population effects are reasonably eliminated. Twelve District Organisers send out appeals to the Press and Radio when new observers are required to maintain the standard of the network.

4. Daily thunderstorm charts

The mapping of individual storm-day areas provides a very convenient opportunity for studying the growth, movement and decay of thunderstorms. A rough examination of the plottings of overhead storm times shows that there is frequently some movement of the storm fronts, and it has been found best to analyse these by means of hourly isochrones. Sometimes a storm can be tracked over the British Isles for between twenty and thirty hours and four or five sets of isochrones can be drawn (Bower 1948a).

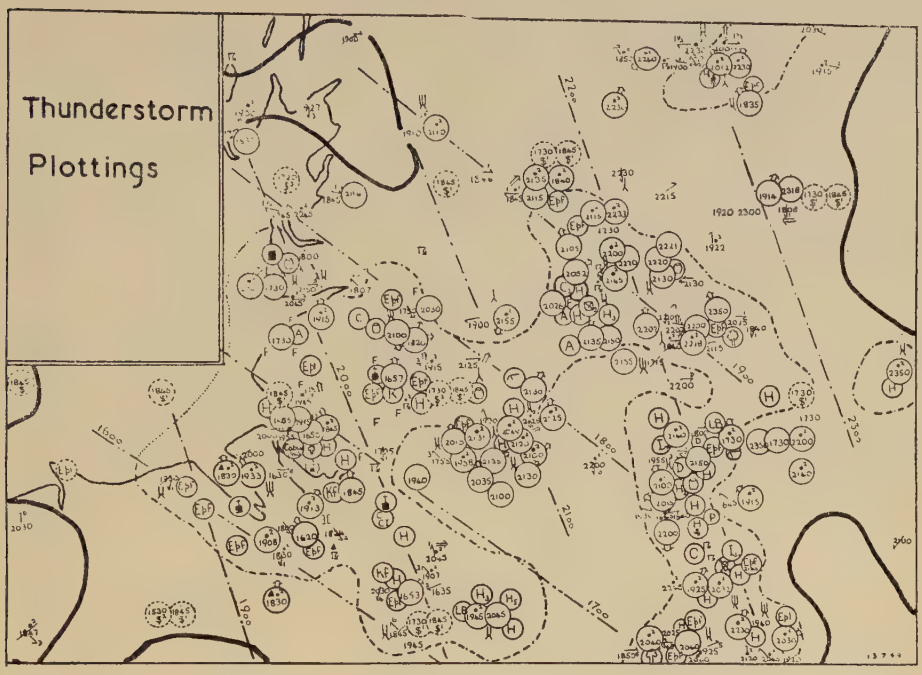

Figure 4. Section of Thunderstorm Chart, showing plotted data and their interpretation.

Scale 30 mi/in.

——— Overhead storm boundary – – – – Damage area boundary

— · — · — Isochrones (first set) — ·· — ·· — Isochrones (second set)

(The letters and symbols inside circles denote various objects struck such as house, factory, steeple, *etc.* Similarly figures give times of occurrence.)

The daily maps normally cover England and Wales on the scale of ten miles to the inch, and are published by the Thunderstorm Census Organisation as *Daily Thunderstorm Charts*. By courtesy of the Controller of H.M. Stationery Office and of the Director, Meteorological Office, selected upper air soundings have been added to these charts, thus facilitating the correlation between the isochrones and the upper winds.

The analysis for 31 July 1948 (Bower 1950a), reproduced in a simplified form in Fig. 5, was the first large-scale examination of damage areas to be published. Three sets of hourly isochrones are identified indicating the movement of the storms generally towards the north and north-north-east. It will be noticed that the storms commence in Devon around 2100 hours on the previous day and can be traced for about twenty-six hours to Fifeshire. Ball lightning was observed at Dyserth, North Wales, and Bamber Bridge, Preston, and chain lightning was recorded at West Kirby, Cheshire. Severe flooding took place at Southport, and at Richmond, Yorkshire, and there were sharp wind squalls in Yorkshire. 383 claps of thunder and 79 lightning flashes were observed in six distinct storms at Wrexham, Denbighshire. There were several deaths.

The analysis for this date was also the basis of a detailed examination and comparison of the results from observers' plots and the radio thunderstorm re-

Figure 5. Daily Thunderstorm Chart for 31 July 1948.

cordings of the Meteorological Office. The evidence obtained by the two methods is complementary. Over land, which is the virtual extent of the observing station network, the plots obtained from observers' records provide a continuity and accuracy much superior to those given by radio methods. Personal observation on the spot seems quite indispensable in the production of large-scale thunderstorm charts and in the delineation of damage areas. When, however, a more immediate, but less precise, indication of the presence of thunder is required, particularly over a sea area, the radio method provides a valuable and convenient

answer. The accuracy of the radio recordings varies slightly at different times of the day, but is of the order of 25 miles ; the accuracy of the boundaries and isochrones derived from the observers' plottings has been found by independent methods to be of the order of 5 miles.

In measuring damage and overhead storm areas, the examination is restricted to the land areas of England and Wales (including the Isle of Man and the Channel Islands). This land area is taken as 58,600 square miles and covers the main Thunderstorm Survey divisions A to M. The damage and overhead storm areas are then expressed as percentages of 58,600 square miles, and the daily severity index for England and Wales is then derived from the ratio of these two percentages.

5. Seasonal variation of thunderstorms

The daily overhead storm and damage areas form the basic data of the Thunderstorm Survey. Period charts are formed by graphical addition (Fig. 6) of the elementary areas by superposition. The method is almost equivalent to an arith-

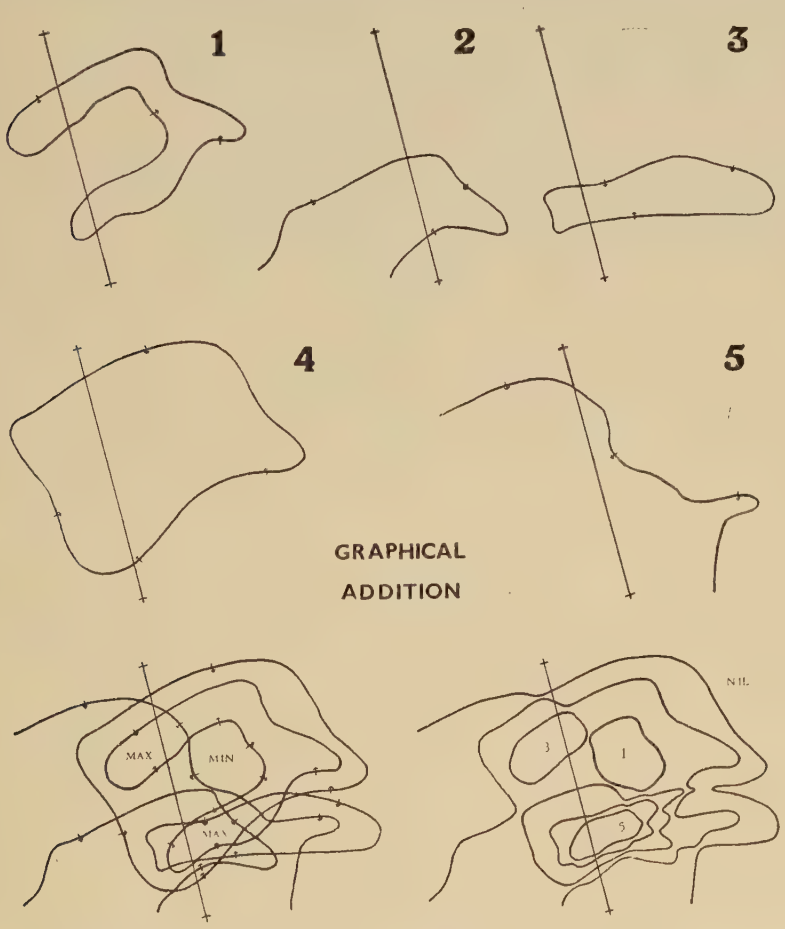

Figure 6. Graphical addition of overhead storm and damage areas.

metical summation at an infinity of points, except for some slight rounding off of corners in drawing up. Summations are usually taken as far as the annual charts by the graphical method.

It is easy to visualise the seasonal rise and fall in thunderstorm activity by inspection of an annual set of charts. The size of the daily overhead storm areas changes through the months (Cave 1923 ; Bower 1927). In 1936 a new method was introduced which involved measuring the actual daily overhead areas and expressing them as a daily percentage of the total area of the country (Bower 1947b). In this way monthly and seasonal means of considerable accuracy have been made available, and direct comparison between seasons and with foreign countries becomes easy. These results are virtually independent of population, and, within reasonable limits, of the size of the country. Calendars of daily figures for certain years have been published (Bower 1947c) and others are available. It has been found that the area summations give better correspondence with damage statistics than do figures for the monthly numbers of days with thunder or lightning, which have also been published. The latter figures are, however, available for a great number of years (Cave 1923) and it is hoped to work them backwards to link up with the twenty-three years Survey (Hands 1893-1915).

6. County thunderstorm surveys

The short-period summations of the daily thunderstorm areas (published as *Period Thunderstorm Charts*) are usually formed by graphical addition. The long-period average maps (published as *County Thunderstorm Surveys*) are usually derived from the basic quarterly charts summed over a period of years at a close grid of points three or four miles apart. They are usually drawn on the scale of two miles to the inch, and a reproduction of the County Survey for Fifeshire (Bower 1948b) is given in Fig. 2.

It is easy to see the great wealth of detail which the analytical methods provide, and how climatological features such as the thunderstorm " shadow " behind hills and the increase in storminess a few miles inland from a coast may be brought out. In some parts of the British Isles " estuary " and " temperature " effects are prominent.

The ground work for the County Surveys for most of Great Britain south of Perth is complete, and the local charts will be worked up as they are required by those professionally interested in the results. It is hard to compare the County Surveys with other analyses because they appear to be the only detailed maps of overhead thunderstorms over long periods ever attempted. But it is useful to record that the various county charts which have been completed agree very well amongst themselves, although the areas are scattered. Such domestic effects as the build-up of storms near certain cities in special geographical situations, and the interplay of estuaries and hills in close proximity, are interesting subjects for further study.

Acknowledgment

Figs. 1 to 6 are reproduced by permission of the Thunderstorm Census Organisation.

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Discussion

Mr. J. F. Shipley : The use of statistics of breakdowns on the main lines of the British Electricity grid to measure the severity of lightning activity is in my opinion an advance on any previous data. The thunderstorm-day statistics which hitherto have been the only reliable data available are unsatisfactory.

I pointed out (1943 *Jour. I.E.E.*, London, **90**, Part I, p. 503) when describing the principles followed by the B.S.I. Committee in the preparation of the British Standard recommendations for the protection of structures against lightning that " thunder . . . . cannot occur unless lightning causes it. Hence, at least one flash per day is included. But one storm, or a series of storms, may last a whole day and each may give rise to many lightning flashes ; in fact, in London 50 flashes have been known to occur per minute, while an average of 19 per minute has been maintained for over six hours. Values of up to 120 flashes per minute have been recorded

elsewhere. Thus the number of days on which thunder is heard per annum is a very rough indication only, but provides the best statistical data we possess as yet."

I had hoped by this time that the results of the Radio Research Group on the number of flashes per storm or per unit time over a specified area might have been known, but I have not yet seen any such information published. When it comes it will probably be a much more reliable criterion than even Dr. Forrest's submission.

May I ask Dr. Forrest if the effect of protective devices on the main grid lines, such as arc-suppressing coils and surge diverters, have been offset in assembling his figures ?

I do think his method gives the most reliable correlation yet possible between the two sets of figures, but if the lower voltage network of the grid, say, the 22,000 volt and the 11,000 volt lines were brought into the assessment, a much better agreement would be obtainable because those lines not only are subject to greater damage by lightning but they provide a much greater and more uniform " spread." Perhaps this might be done in the future.

Dr. Forrest said there was a discrepancy in the correlation of the winter figures. Might not this be due to the fact that only one station in S.W. England was taken (*i.e.* Long Ashton) ? Some years ago I was discussing the frequency and severity of lightning in Cornwall with the Electricity Supply Authority there. They complained of excessive damage in winter, and I found that the storms at that period followed a curved route from Iceland past the West of Ireland and came in over Cornwall from the west. The storms derived their energy from heat and moisture picked up from the warmer Atlantic sea surface. Had the recording station been at Haye, for instance, rather than at Long Ashton there might have been greater agreement.

I do not like the author's comment on " severity." Separate single breakdowns of similar character caused by lightning flashes may cause vastly divergent monetary losses which are sometimes greater if the indirect losses are taken into account. For instance, a discharge may puncture a line insulator. Normally this will put one line out of service but if there is only a single feeder line such a breakdown can cause substantial expense with loss of revenue. Quite a normal figure would be £75 for one hour's breakdown.

If, however, the puncture of that insulator resulted directly in a power station equipment being burned out (as has actually happened), the direct loss might not be less than £100,000 for the equipment, plus say £25,000 for loss of revenue ; or if a flooded mining paddock were the result of a line breakdown owing to the electrically driven de-watering pumps not being available, there might be a direct loss of £1,200 plus a loss of output and hence of revenue of £7,500. These are only rough figures but they indicate that one cannot predict the financial loss, *i.e.* the true extent of the damage, on the basis of character of breakdown.

Mr. D. F. Oakeshott : Lightning recorders of the type devised by Dr. J. S. Forrest (1946, *Weather*, p. 148) should be capable of giving an idea of thunderstorm severity and accordingly the records taken at Horsley for January, 1945 were examined to see whether they could account for the very high number of faults which occurred in a month with only two thunderstorm days. While the

number of strokes per hour (above an arbitrary level) was quite high, it was not exceptionally so and did not even coincide with the maximum count that was found on other occasions. However, the severity of a storm should be proportional to the number of strokes to earth and the existing apparatus does not differentiate between these and cloud-to-cloud discharges.

It will be interesting to see whether records taken with Schonland's " Kerauno-meter," which does give some indication of this difference, furnish a measure of thunderstorm severity in line with breakdown data. Chart-speeds of approximately four inches per hour should make it possible to resolve all the flashes recorded and hence give the frequency of flashes to earth.

Mr. P. J. Ryle : Dr. Forrest's main conclusion is that the annual lightning breakdown rate on the Grid transmission lines is not directly proportional to the number of thunderstorm-days per year, but to some power of the latter in the region of 1·4 to 1·9.

In his paper " The Performance of the British Grid System in Thunderstorms," (1949, *Jour. I.E.E*), the author gave figures for the average annual thunderstorm days as 13 for Great Britain and 30 for South Africa, a ratio of about 2·3 to 1. Reliable statistics are available for the lightning breakdown rates on extensive high voltage transmission systems in South Africa, which indicate that the average lightning breakdown rate, per mile of line, is of the order of 10 times that in Great Britain. The South African lines are not of quite the same designs as those in this country, and other factors such as average electrical resistivity of the earth, and average height of lines above sea-level, *etc.*, are somewhat different, so that direct comparison is not strictly justifiable. However, if we take the above figures, the " Forrest index " would be about 2·7. No particular quantitative significance should be ascribed to this, but it does at least tend to reinforce strongly the author's main conclusions.

One is led to wonder what physical causes give rise to the very considerable variations in general lightning severity from year to year, as illustrated in Fig. 1 in the paper. I have sometimes been tempted to trace a slight correlation between both general level, and range of annual variation, with the approximately 11-year sunspot cycle, but understand that long-term meteorological records do not support this. Fig. 1 also tends to show an approximate 2-year cycle, relatively good and bad years more or less alternating, but it is difficult to imagine any cause for such a cycle. Of course, as far as breakdown rates are concerned, many more years of Grid lightning statistics would be necessary before any conclusions as regards cyclical effects could be confirmed or otherwise.

Dr. R. H. Golde (*partly communicated*) : Dr. Forrest examines a problem which is of greatest interest not only to the meteorologist, but also to the research engineer concerned with the performance, under lightning conditions, of electrical transmission lines.

On the occasion of Dr. Forrest's presentation of his earlier paper to the Institution of Electrical Engineers in December 1949, I showed Fig. 1 in which the annual numbers of lightning faults on the British Grid system (as obtained from Dr. Forrest's data) are compared with the general isokeraunic levels of the corresponding years. Fig. 1 is based on an average from 250 observation stations, in the general area

covered by the British Grid, for which the relevant information is available in the *Monthly Weather Report* of the Meteorological Office. I should like to ask Dr. Forrest why he has confined his examination to 8 stations only since local storms outside the range of these stations remain unaccounted for, while storms affecting more than one station on any one day are counted separately. Thus, 7 cases in his Table I show a number of monthly thunderstorm days exceeding the number of days in that month.

Dr. Forrest states that " overhead-line breakdowns probably provide the best available measure of thunderstorm severity." This, of course, only holds if the likelihood of a breakdown occurring as the result of a direct lightning stroke is everywhere the same. This is not strictly the case in view of local variations of the earthing resistance of transmission towers since a higher proportion of lightning flashes are known to cause power system breakdown in regions of high soil resistivity.

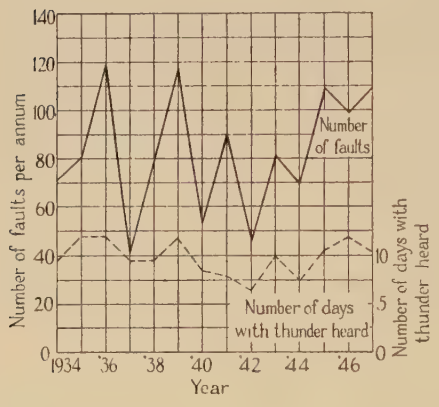

Figure 1. Correlation between number of lightning faults on British Grid and thunderstorm activity.

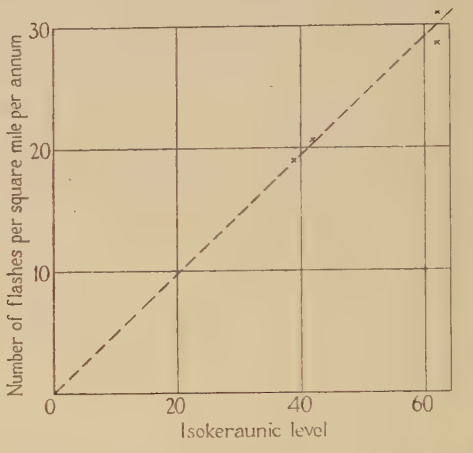

Figure 2. Correlation between number of lightning flashes to earth and isokeraunic level.

A better measure of thunderstorm activity appears to be the actual number of lightning flashes to overhead lines. Thus, from 1,506 lightning flashes recorded on four American transmission lines the corresponding number of lightning flashes to earth per square mile per annum have been derived (Golde 1945a) and are indicated by the crosses in Fig. 2. Although it would be premature to draw final conclusions from four cases, Fig. 2 suggests a proportional relationship between the number of lightning flashes to earth and the isokeraunic level of the area involved. This preliminary conclusion seems to be strengthened by an independent investigation (Golde 1945b) in which the number of lightning flashes to earth in England was found to be about 6 per square mile per annum, a number which agrees very well with the figure suggested by the straight-line law of Fig. 2 if it is remembered that the general mean isokeraunic level of England is about 11 or 12.

Summarizing our present-day knowledge of the frequency of occurrence of thunderstorms and their severity, I would be inclined to say that we are just be-

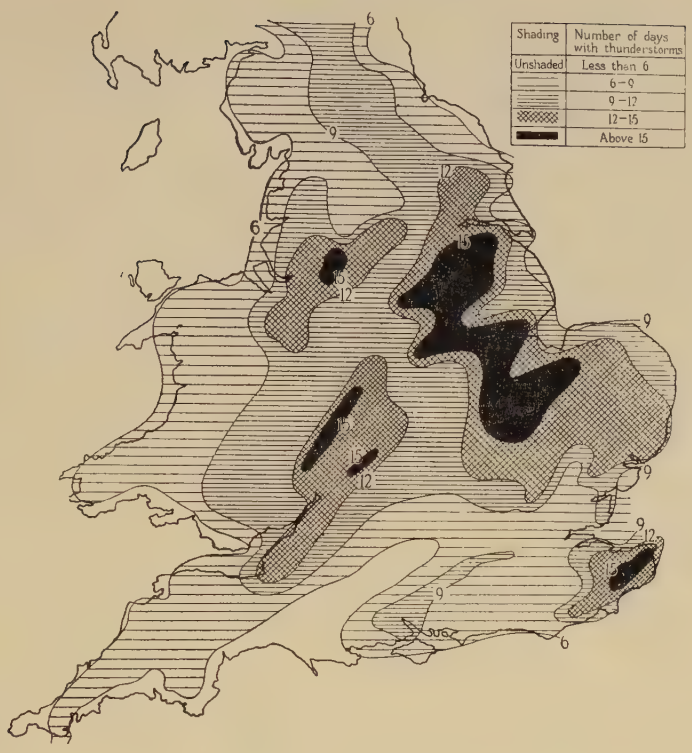

Figure 3. Distribution of thunderstorms over England and Wales, 1949.

ginning to feel our way, with little prospect of finality in sight. In these circumstances, papers such as that presented by Dr. Forrest are most opportune, particularly in stimulating interest in further investigations.

With this point in view and in connection with a statistical investigation of lightning faults on British lower voltage lines, the Electrical Research Association have initiated a census of thunderstorm activity and particularly of the frequency of lightning flashes to earth. This investigation is effectively supported by the Meteorological Office and derives further benefit from co-operation with the Thunderstorm Census Organisation. The data collected last year have made it possible to prepare a map showing the isokeraunic lines for England and Wales (see Fig. 3). The investigation has now been extended to cover the southern part of Scotland and, if continued for a sufficiently long period, may assist in increasing our knowledge in a subject which is both of theoretical and practical importance.

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Mr. E. Gold : I suggest that Dr. Forrest should indicate how far apart two thunderstorms have to be in order that they should be separately recorded by a " breakdown " on the grid-system.

Mr. J. S. Sawyer : The secondary maximum of thunderstorms in the early

morning shown in Fig. 3 of Dr. Forrest's paper might be due to maritime storms in western coastal districts which had a maximum at that time. I would like also to comment on the isochrones of thunderstorms displayed by Mr. Bower which show two storms advancing in different directions over the same area. An investigation by the India Meteorological Department, of early summer thunderstorms in Bengal (1944, *Tech. Notes.*, Met. Dep., India, Bombay, No. 10) has shown similar features. This suggests that the movement of thunderstorms is not entirely controlled by the general distribution of upper winds which would be expected to be much the same over two storms occurring within the space of 2 or 3 hours.

Dr. F. J. Scrase : Dr. Forrest draws attention to the secondary maximum in the breakdown frequency in the early morning and notes that this is not shown by the observations of " thunder heard " at Kew Observatory. This is probably because the observers at Kew are not normally on duty in the small hours of the morning. A secondary maximum between 4h and 6h G.M.T. is, however, shown in the diurnal variation of point discharge recorded at Kew (Whipple and Scrase, 1936, *Geophys. Mem.*, London, No. 68).

I wonder whether Dr. Forrest has made any estimate of the ratio of the frequency of breakdowns to that of lightning flashes occurring over the whole area served by the grid. The records of lightning flashes obtained with the point discharge apparatus at Kew led to an estimate of about five flashes of all types per square mile per year. Taking the area of the country served by the grid to be 50,000 square miles gives a total of 250,000 flashes per year, of which probably a little more than half are to earth. Since the average number of breakdowns per year is about 100, it appears that roughly one earth flash in 1,500 over the whole area causes a breakdown ; but the great majority of the flashes will not, of course, be withing striking distance of the lines.

The line drawn through the points in Dr. Forrest's Fig. 4 does not appear to me to be the best fit. I suggest that it should be tilted upwards through an angle of about 10°, in which case the constant k would be 0·00013 and the severity index 2·9.

Mr. L. Jacobs : The explanation of the distribution of thunderstorms shown in the excellent maps prepared by Mr. S. Morris Bower presents many problems. Similar problems have been investigated, in great detail, by the American Thunderstorm Project (Byers 1949, 1950). In a cursory examination of Mr. Bower's maps I noticed two points which could be explained by the American work. The first was the marked maximum of thunderstorm activity shown some 10 miles inland in Ayrshire (where the ground is generally flat except in the extreme north and south). This is probably largely due to the extra convergence with the onset of the afternoon sea breeze, an effect also found in Florida, where sea breezes come in from both sides. The second was the mechanism for the steady advance of thunderstorms, shown on many of the maps. While this may be partly frontal, or due to a large area of thundery rain, the travel or redevelopment of convective thunderstorms appears to be helped by the uplift due to the cold outflowing air of an existing thunderstorm. The American work showed that the greatest frequency of new thunderstorm-cell development was in the area between two existing cells, whose edges were three or less miles apart, while a three-mile band downwind was next in importance. They also noted however, that there were cases in which

one or a cluster of new cells came into existence, as indicated by radar echoes, almost simultaneously with the initial cell, indicating preferred regions of updraft, rather than the time-consuming process of under-running cold air.

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Mr. F. Horner : Mention has been made of the possibility of using radio means for measuring the frequency of occurrence of lightning flashes in the vicinity of the observing station, and thus obtaining a measure of thunderstorm activity. It would be of interest to know what, in the opinion of meteorologists, should be the range of a single recorder. For example if the British Isles were covered by a network of 100 stations, should each recorder register the flashes within the radius of a few miles covered by the present listening technique, or should the areas covered by adjoining stations just overlap, or is there some other optimum area ? The coverage required would have an important bearing on the technique adopted.

Mr. W. N. Lavis (*communicated*) : One cannot but admire Dr. Forrest's courage in dealing with a subject so full of meteorological and electrical variables. Attention has already been drawn to some of these and to the wideness of the definition " thunderstorm day." Other factors are summarised below :—

Even with the more precise " overhead storm day " one would have to reckon with the spectacular inter-cloud discharge full of meandering horizontal lightning which looks impressive but does little or no harm.

Wooded or built-up country and the geology of the country are further variables before the electrical ones can be classified. The author has said elsewhere (Forrest 1949) " the incidence of faults on power lines is influenced by factors other than thunderstorm severity, *e.g.* soil resistivity."

If an open stretch of line is struck, the surge peak may become attenuated and rendered harmless while both Hagenguth and Golde (1946) have drawn attention to the shortcomings of magnetic-link interpretation of surge currents.

Flash-over does not always occur on a line struck by lightning and when it does, the damage may be so slight as to preclude exact location and assessment.

The same stroke to a line in a built-up area will be nearer a sub-station and therefore more likely to produce a fully documented fault. Thus it is hard to see how country lines are properly represented in terms of thunderstorm statistics.

In Fig. 1 one wonders how much improved techniques, evacuation of population and dispersal of industry have contributed to the depressing of the breakdown graph. The progressive improvement in transformer design and protection from lightning in recent years, as mentioned by Forrest (1949), will minimise the effect of storms and reduce their apparent frequency and severity as shown by breakdowns.

The " uniformity " of the Grid is restricted to the meaning that the lines tend to join population centres by the shortest possible route and one feels that winter west-coast storms would be quite inadequately represented in faults.

Crossings of navigable waterways are usually at especially high levels (*e.g.*

the lower Thames crossing) and one obtains the special influence and complication of extra high pylons in the presence of water near the coast — a physical study in itself. Height alone will increase the chance of lightning stroke and give rise to the local accentuation of severe storms in meteorological statistics prepared from unweighted electrical fault records.

Tower footings vary with the nature of the traversed ground with corresponding differences in resistance to earth of individual pylons. Again, sections of line are particularly exposed while others may run for miles quite inconspicuously through wooded, sheltered country.

Taking into account the known distribution and travel of thunderstorms, one feels that to work up thunderstorm data from heterogeneous electrical faults is a process fraught with too many uncertainties incapable of elimination by even an elegant mathematical concept such as the " severity index."

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Forrest, J. S.	1950	*Proc. Inst. E. E.*, London, **97**, Pt. II, p. 345
Golde, R. H.	1946	*Ibid,*. **93**, Pt. II, p. 559.
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Mr. R. Butler (*communicated*) : Dr. Forrest is to be congratulated on presenting a valuable and interesting paper not the least so because there are too few papers of this sort detailing investigations of a similar heuristic nature.

That the index is the proper criterion for severity may be questioned by some, but if it is accepted as adequate for the moment, then some comment seems called for with regard to the suggested value for S when considering the annual totals for N.

The author has said that the method of least squares gives

$$N = \cdot 017\ T^{1 \cdot 86}$$

From the purely statistical point of view this is no doubt satisfactory, but it is open to the criticism, that what is sought presumably is not the best value for N that can be derived from the observations available for T, but the best value for S that can be derived from the observations available for both N and T.

From the regression of $\log N$ upon $\log T$

$$N = \cdot 0152\ T^{1 \cdot 88}$$

whereas from the regression of $\log T$ upon $\log N$

$$N = \cdot 00000726\ T^{3 \cdot 53}$$

and it is this marked divergence that renders the proposed value for S impugnable.

The number of observations available is comparatively small, but the correlation coefficient of 0·729 calculated in conjunction with the regression equations just mentioned indicates that closer limits might be found.

Maintaining the assumption that a power relation is required one can plot $\log (NT)$ against $\log N$ or against $\log(NT^{\frac{1}{2}})$, operations which are typical of a technique developed by the writer of this note to deal with data similar to those available to the author of the paper, and it will be found that the sporadic appearance of the points as plotted directly, is replaced by a much more orderly array and it can be demonstrated that

$$N = KT^3, \text{ approximately.}$$

a more definite value of this order for S being calculable by normal methods using the sophisticated terms.

In estimating the degree of confidence with which this value for S should be received, the number of observations available has to be kept in mind and, as a confirmation of the power relation, possible implications of the result of the manipulation of the data should not be overlooked.

Mr. L. C. W. Bonacina : After reading Dr. Forrest's paper, about a week ago, I looked up the word fulminant in the Oxford Dictionary and found that its first meaning was a " thunderbolt " — which to a meteorologist should just signify damage caused by lightning. We may recall King Lear's " oak-cleaving thunderbolts " as indicating how deep-rooted the word thunderbolt is in the English countryside. I suggest accordingly that Dr. Forrest's " severity index " might very well be called a " fulmination index " in relation to the context of his paper.

In Britain, as in most parts of Europe, the months of May, June, July and August stand out conspicuously in thunderstorm statistics, and I am interested in Dr. Forrest's remarks concerning the relative figures for May and August. Although August is further from the summer solstice than May, the high moisture content of the warm air of the later summer is no doubt an important factor in August, and the same factor helps to keep up the number of thunderstorms to some extent in September or even October.

I do not think the March minimum in Dr. Forrest's statistics accords very well with common experience or with other statistics.

Mr. S. Morris Bower (*partly communicated*) : The basic definition of a *thunderstorm-day* as any civil day on which *thunder* may be heard is convenient but very weak. It is easy to see (Fig. 1) how under normal conditions, three or more *thunder-heard-days* may be recorded in a short period in a place where there has been no overhead storm. We have worked in Fig. 2 the annual variation of days with thunder or lightning over the whole of England (Bower 1947c) for the years 1934 to 1947 against the figures for breakdowns on the Grid (Forrest 1949) and have obtained the rather alarming correlation coefficient of 0·17. For example, 1936 gives 146 thunder-days and 146 faults, while 1937 gives 140 days and only 49 faults ; and again 1941 gives 137 days (Bower 1949a) and 96 faults while 1942 gives 130 days and only 48 faults. It is clear, as Dr. Forrest points out in Section 4, that little justice to thunderstorm severity is done by thunder-day statistics, and, indeed, it seems extremely doubtful whether any significant relation between the two sets of data exists at all. In this light it is hard to comprehend the introduction of the proposed severity index based on thunder-heard-day figures.

Dr. Forrest's choice of eight stations is clearly heavily weighted in favour of centres of population ; only Eskdalemuir could be properly regarded as being in a thinly peopled area. Grid breakdowns, which are mainly in populated districts, may therefore be expected to show better agreement with these eight stations than with statistics for the whole country. Many hundreds of plottings of lightning damage to animate and inanimate objects have been made for the *Thunderstorm Survey* maps, and it will be seen that damage to the Grid only represents a small and very variable proportion of the cases (Bower 1950). It would be very hard

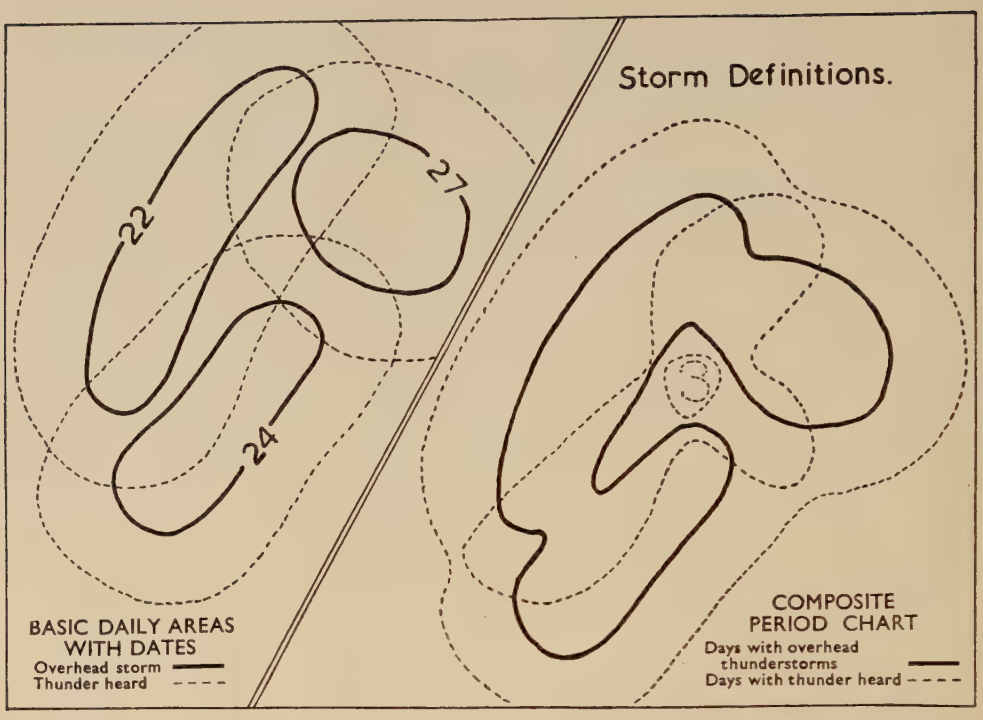

Figure 1. Definitions of overhead thunderstorm and thunder heard and resulting period charts.

to accept that overhead-line breakdowns provide the best available measure of thunderstorm severity as suggested in the Introduction, unless an immediate local indication when a power line is actually struck is all that is required.

The daily overhead thunderstorm areas have been mapped in detail for this country for about twenty five years, and monthly and seasonal summations of the areas have been published for certain periods (Bower 1947a). These summations have been roughly averaged and sketched in Fig. 3 and give a closer approximation to Grid breakdowns than do thunderstorm-days.

Recently the new conception of " damage areas " has been introduced and these have been drawn out daily and summed to form a Damage Map for the year ending September 30th, 1949. It is interesting to compare this map with that for overhead storms, and it would seem that the ratio between the damage area and the corresponding daily overhead area would provide a very much better measure of thunderstorm severity than anything derived from figures restricted to Grid breakdowns, or embodying the obviously weak conception of days with thunder heard.

With regard to seasonal variation, Dr. Forrest's selected stations do not show the winter maximum of thunder in January, which is conspicuous in the averages for fifteen years (Bower 1949a) ; this may account for the anomaly mentioned in Section 4. The summer figures in his Fig. 2 tend to overshadow the winter ones by their relative magnitudes, but it is interesting to note that the aggregates of thunder-days at the eight stations approach so closely to the totals of breakdowns. We have therefore worked the average monthly number of days with thunder or

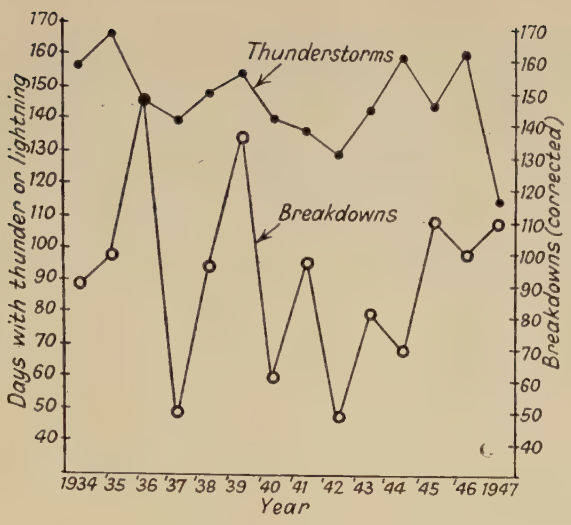
Thunderstorms
Breakdowns
Days with thunder or lightning
Breakdowns (corrected)
Year
1934 '35 '36 '37 '38 '39 '40 '41 '42 '43 '44 '45 '46 1947

Figure 2. Comparison between annual number of grid breakdowns and annual days with thunder or lightning in England.

lightning in England over fifteen years (Bower 1949a) against the breakdowns (Fig. 4) and obtained a correlation coefficient of ·88. Coupled with Dr. Forrest's coefficient of ·97, one wonders, however, how much these high coefficients are due to the very pronounced seasonal variations in both days and breakdowns rather than to a basic relationship. A much more valuable comparison would seem to be given by the annual figures which in the circumstance mentioned above yield the low coefficient of ·17.

It appears to be quite impossible to accept Dr. Forrest's statement in Section 5 that " meteorological data on the diurnal variation in the frequency of thunder are not available to enable a detailed comparison to be made with the breakdown data," as the figures from an analysis of about ten thousand records of times of storms were published some seventeen years ago (Bower 1933). The results were republished in the same volume as the histogram for Kew mentioned in his Section 5. One would also have hoped to see very considerably more than 63 items used in an attempted classification into 24 time divisions in the diurnal variation of winter breakdowns graphed in Dr. Forrest's Fig. 3.

Comparing the meteorological and breakdown data (Fig. 5) the agreement between the general early morning maxima around 0400 to 0500 is good, but the afternoon maximum between 1400 and 1500 appears some two hours later in the

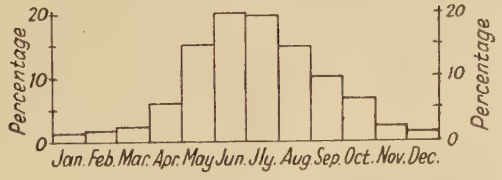

Figure 3. Mean seasonal frequency of daily thunderstorm areas (England).

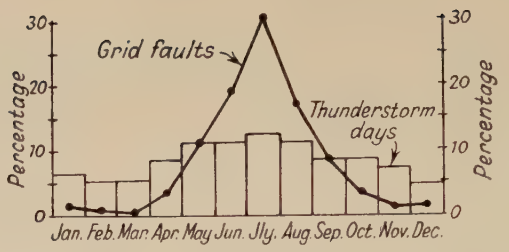

Figure 4. Seasonal frequencies of grid faults and thunderstorm days (England).

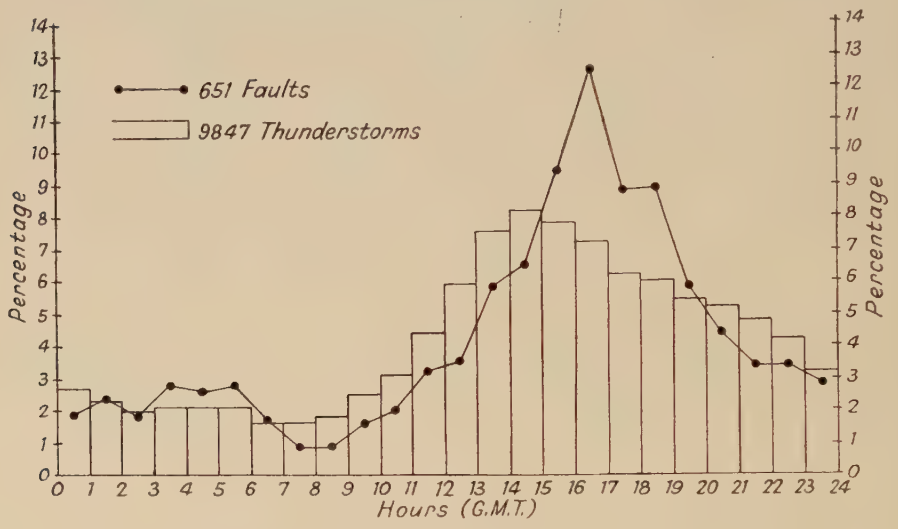

Figure 5. Comparison of diurnal variations of grid faults and thunderstorms.

breakdown data (Forrest 1949). This discrepancy might be resolved by a study of the changes in diurnal variation across the country and taken in conjunction with the actual distribution of the Grid lines, ignoring any supposed uniformity in distribution. One also wonders whether any time lag in reporting breakdowns may occur towards the end of the normal working day (Bower 1947b).

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	1947b	*Met. Mag.*, London, **76**, p. 255.
	1947c	*British Thunderstorms*, Huddersfield, **2**, Pp. 107 and 121.
	1949a	*British Thunderstorms*, Huddersfield, 22nd Summary, Table 3.
	1949b	*Thunderstorm Census Organisation*, Huddersfield, Research Publication, 49/5.
	1950	*Quart. J. R. Met. Soc.*, London, **76**, p. 461.
Forrest, J. S.	1949	*Proc. Inst. E. E.* London, (In publication).

Dr. J. S. Forrest (*in reply, partly communicated*) : I am interested in Mr. Morris Bower's detailed and painstaking analysis of the frequency and geographical distribution of thunderstorms, but I am doubtful if the degree of detail shown on his maps is justified and if much of it has any significance on a long-period basis.

Regarding the relation between annual thunderstorm-days and breakdowns, the stations used for the thunderstorm-day observations were, of course, selected,

as stated in the paper, to represent the parts of the country covered by the Grid network, and a highly significant correlation (0·74) was found ; the chance of this result being obtained from an uncorrelated population is about 1 in 1,000. Dr. Golde, investigating the question independently and using observations from 250 stations, also obtained a significant correlation. It is noteworthy that Dr. Golde's curve based on 250 stations is quite similar to my curve for eight stations ; both follow the same trend and have about the same range of variation. This confirms that the eight stations are adequate and that there would have been no advantage in using observations from a much larger number of stations. It is clear, however, from both investigations that the number of breakdowns is a function of the thunderstorm-days in the area in question ; I think, therefore, that the negative result obtained by Mr. Morris Bower must arise from the particular figures he has used for thunderstorm frequency.

With reference to the diurnal variation, the information required for a detailed comparison with the power system data is the number of occasions on which thunder was heard in each hour (or two hours) for 1940-1947 at the eight stations used for the annual and seasonal data ; as far as I know this information is not available. There is no question of any " time lag in reporting breakdowns " ; a breakdown is indicated automatically in the control room and the time logged correct to the nearest minute.

In reply to Mr. Shipley, the figures given in the paper are for the actual number of breakdowns and no attempt has been made to allow for the effect of protective devices. The important point, however, is that no major changes were made to the Grid in the period under review. I agree that useful information could be obtained from the lower-voltage lines on which the number of breakdowns per mile of line is relatively high. Reliable data are not, however, available for past years, as standard types of construction and methods of recording breakdowns have not been used throughout the country. Steps are now being taken to compile reliable statistics. In the paper, I have taken the number of breakdowns, not the cost of the damage, as a measure of severity. The financial loss incurred, as Mr. Shipley points out, varies greatly with the circumstances and would not be a good measure of severity. My reference to the amount of damage was not meant to imply the financial amount. What is really required is some electrical method of recording the number of flashes to earth per square mile, and Mr. Oakeshott has given an indication of the lines of investigation which we are following. Unfortunately, it seems doubtful if the Keraunometer will give a reliable measure of the number of flashes to earth because the principle of operation of this instrument depends on rather an idealised structure of the thundercloud. Regarding the winter storms referred to by Mr. Shipley and Mr. Sawyer, the relatively high breakdown figure for January is largely due to one storm on the night of January 18-19, 1945, mainly in the North East coastal area of England.

Mr. Ryle's comparison between Great Britain and South Africa provides interesting confirmation of the need for using a severity index. As he appreciates, it is not permissible to assume that the severity index found from the British data could be applied to other parts of the world. Sunspots have important electrical effects on the upper atmosphere but attempts to find correlations between the

sunspot cycle and weather variations have in general been unsuccessful. In the present case, the correlation between the annual breakdowns and the sunspot numbers (Zürich) is 0·25, which is not significant for 14 pairs of observations.

In reply to Mr. Gold, the average length of the Grid lines is 20 miles for the 132 kV lines, and 10 miles for the 33 kV lines. In general, therefore, two storms 10 or 20 miles apart (or a single storm covering 10 or 20 miles) could cause two separately recorded breakdowns on different lines.

I am interested to hear from Dr. Scrase that the Kew point-discharge records exhibit the secondary maximum between 4 hr and 6 hr G.M.T. It is also significant that the afternoon maximum point discharge occurs between 16 hr and 18 hr, in agreement with the power system data. I agree that, considering the whole area of the country, only one flash in several thousand to earth causes a breakdown. The effective area of the Grid system, assuming a semi-vertical angle of protection of 45°, is however only about 100 square miles. Taking Dr. Scrase's figure of 3 flashes to earth per square mile per year, we find that one flash out of every four which strike the lines causes a breakdown. This is only a rough general estimate as the figure varies with the system voltage, *i.e.* with the line insulation.

With regard to the relation between breakdowns and thunderstorm-days, I have considered thunderstorm-days to be the independent variable and accordingly have drawn in Fig. 4 (and in Fig. 5) the regression of log N on log T. The other regression line has a greater slope corresponding to a severity index of 3·5 as shown by Mr. Butler. The single line which best represents the law relating log N and log T, assuming both variables subject to error, would have a severity index of about 3 as suggested by Dr. Scrase and Mr. Butler. It is doubtful if the data justify an attempt to calculate the severity index precisely ; the main point is that the number of breakdowns is not directly proportional to the number of thunderstorm-days. In this connexion Dr. Golde's finding that the number of flashes to earth varies directly with the isokeraunic level is difficult to reconcile with the results given in my paper. More experimental data are clearly required to clarify the relation between thunderstorm-days, flashes to earth, and breakdowns on power lines.

I thank Mr. Bonacina for his etymological suggestion. A minimum thunderstorm-frequency in February or March is not uncommon near the coast, for example at Cardiff.

I appreciate very fully the limitations cited by Mr. Lavis of both thunderstorm-days and breakdowns as measures of severity, and I have drawn attention to these limitations in my paper. It should be noted however that a breakdown on a Grid line is fully recorded irrespective of whether the incident is near to or remote from a substation. Improvements in transformer design and other factors have led to a reduction in the number of failures, but as 94 per cent of the breakdowns have occurred on the overhead lines, it is considered that changes in transformer design and protection can have had little effect on the data given. I think Mr. Lavis is unduly pessimistic about the possibility of utilizing power system records to provide thunderstorm statistics. Surely it is encouraging to find that the Grid data have in a comparatively short period given us a picture of the annual, seasonal, and diurnal variations of thunderstorms which is in general agreement with existing meteorological statistics, but has been obtained quite independently.

The measurement and recording of the heat flux into the soil

By E. L. DEACON
Section of Meteorological Physics, C.S.I.R.O., Australia

(Manuscript received 29 June 1950)

Summary

Relatively simple instruments for measuring the heat flux into or out of the soil are described together with methods of calibration. One form consists of a suitable metal disc of sandwich construction producing a thermal e.m.f. proportional to the heat flux through the disc, which is placed in the soil just below the surface.

Details are also given of another form of flux plate which is suitable for continuous recording using a thread recording galvanometer.

1. Introduction

The study of the heat balance at the earth's surface involves the measurement of many factors, some of them requiring rather refined and troublesome techniques. Any simplification that can be made in the method of measuring any one of these quantities is therefore much to be desired. With this in mind, a simple method of recording the flux of heat into or out of the soil has been devised.

The method depends on the fact that the temperature difference between the two surfaces of a relatively thin plate of suitable material, inserted just under the soil surface and parallel to it, is proportional to the heat flux through the lamina into the soil beneath. The material of the plate is chosen to have a thermal conductivity rather greater than that of moist soil so that it presents no barrier to the passage of heat.

After the method had been shown to be workable it was found that Falckenberg (1930) had used a similar technique. It is evident, however, from the literature that meteorologists in English-speaking countries have so far not taken advantage of Falckenberg's work but have resorted to the laborious method of taking soil temperature profiles together with the heat capacities of soil samples from various depths. It has accordingly been thought worth while to give an account of the present work, especially as the instrument, in its second form, has been made continuously recording and the construction and calibration considerably simpler than with Falckenberg's design.

2. Disc type of heat flux plate

This flux plate, shown in section in Fig. 1a, is a disc 5 cm in diameter consisting of bismuth cast between two discs of copper. The copper plates have to be lightly tinned for the bismuth to adhere. They are made oversize in the first place, the disc being finished by turning to the correct diameter and by lapping the top and bottom surfaces. A guard ring 9 cm diameter of similar construction surrounds the disc but is separated from it by a thin strip of insulating material.

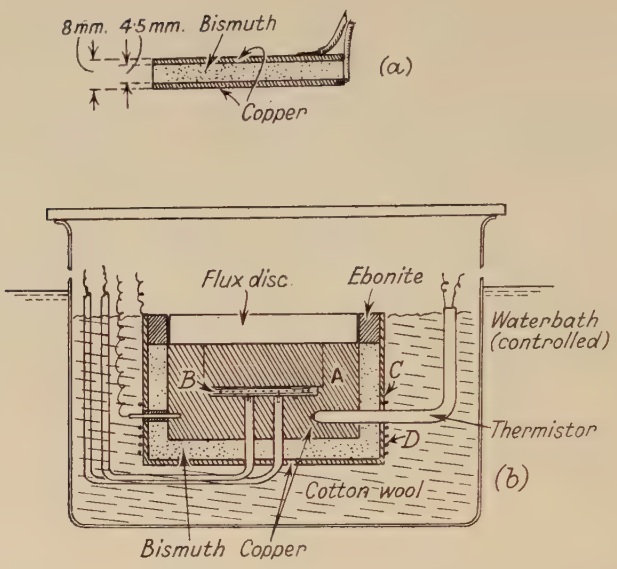

Figure 1. (a) Section of flux disc and (b) calibration arrangement.

The bismuth-copper sandwich produces a thermal e.m.f. proportional to the temperature difference between the copper discs. The bismuth-copper combination was chosen for its high thermo-electric effect and for the low thermal conductivity of bismuth (0·02) as compared with other metals. The copper plates also serve to produce uniform temperatures over the two faces of the disc. This type of disc gives an e.m.f. of around 60μV for a heat flux of 1 cal cm^{-2} min^{-1} and the resistance is very small so that, with a galvanometer of sensitivity around 1 cm/μV, a heat flux of 0·3 cal cm^{-2} min^{-1}, which often occurs on clear days in summer, gives a deflection of some 18 cm.

While this account was being prepared a paper by Hatfield and Wilkins (1950) came to hand in which a heat flux disc for measuring the heat flux through warship bulkheads is described. This uses a similar sandwich of copper and a tellurium-silver (2 : 1) alloy. This combination produces an exceptionally high thermal e.m.f. so that a disc only 1·3 mm thick produces 440μV for 1 cal cm^{-2} min^{-1} heat flux. It is likely that this form of disc, given a suitable protective coating would be very suitable for measuring the heat flux into the soil. The method of construction whereby copper gauze is bonded to the tellurium-silver disc by hot pressing, is reported to give discs of more uniform calibration characteristics than were obtained with the bismuth-copper discs in the present work, which were found to vary by as much as $\pm$30 per cent. between different specimens owing apparently to the need for tinning the copper before casting the bismuth.

3. Method of calibration

The discs were calibrated using the apparatus shown, in section, in Fig. 1b. A cylindrical copper core A containing a constantan heater coil B is separated by a uniform bismuth layer from a coaxial copper pot C on which there is a second

heater winding D. When the heater currents are suitably adjusted there is no net flow of heat between core A and pot C as indicated by zero e.m.f. between A and C and all the heat developed in heater B passes through the disc to be calibrated. Good thermal contact between the disc and the lapped top surface of the core is ensured by a trace of vaseline. Adjustment of the current through the outer heater winding is made by steps allowing several hours to elapse, each time, for the steady state to be restored as the time constant of the system is large. The temperature of the core is measured using a "Stantel" thermistor Type 2311/300 and readings of the galvanometer connected to the disc are only accepted when the core temperature has not changed during a period of 30 minutes by more than 0·02°F. This precaution is necessary as otherwise the rate of heat accumulation in the core, *etc.*, is not negligible compared with the flux being measured.

The galvanometer reading appropriate to no heat flowing between A and C is most conveniently obtained by graphical interpolation between readings obtained with values of the outer heater coil greater and less than that for no heat escape.

The calibration of a heat flux disc of this type was checked by measurements of the heat flowing into a bed of dry sand exposed to strong sunshine for several hours, temperature profiles in the sand under the disc being taken at intervals and the heat flux evaluated from them and the measured heat capacity of the sand. The heat flux so measured was only 5 per cent. different from that indicated by the flux disc using the laboratory calibration.

4. Recording heat flux plate

An easily constructed type of heat flux plate using multiple junction thermocouples was devised suitable for recording on a Cambridge Thread Recording Galvanometer of resistance 17 ohms and full-scale deflection from centre zero for 22μA. Glass was chosen as having a suitable thermal conductivity and imperviousness to moisture. The construction is shown in Fig. 2a. A glass microscope slide $3\times1\times0{\cdot}06$ in. has notches ground in the edge to position the end turns of multistrand copper wire. Between these, 30 turns of No. 36 S.W.G. bare constantan wire were wound, openly spaced, and after degreasing were copper plated on one half of the width of the slide, on both sides, by half immersing it in the plating solution (Fig. 2b), a plating of about 0·07 mm thickness being applied. Shellac applied to the half of the slide not being plated prevents trouble arising from creeping of the solution. This application of Wilson and Epps (1920) technique results in 30 pairs of thermojunctions with alternate junctions on the centre line of the top and bottom surfaces of the plate, being formed with greater neatness than would be possible without considerable effort by the usual methods. The plate is finished by two applications of a good tropical insulating varnish, a layer of aluminium foil over the thermocouple winding and two more coats of varnish. Polystyrene sleeving was used to insulate the flexible leads, the end of the sleeving being split to go over the copper end turns (Fig. 2c) and secured by a binding of thread and more varnish.

These glass flux plates have an electrical resistance of about 4 ohms and produce an e.m.f of around 1200μV for 1 cal cm^{-2} min^{-1} heat flux. Calibration has so far

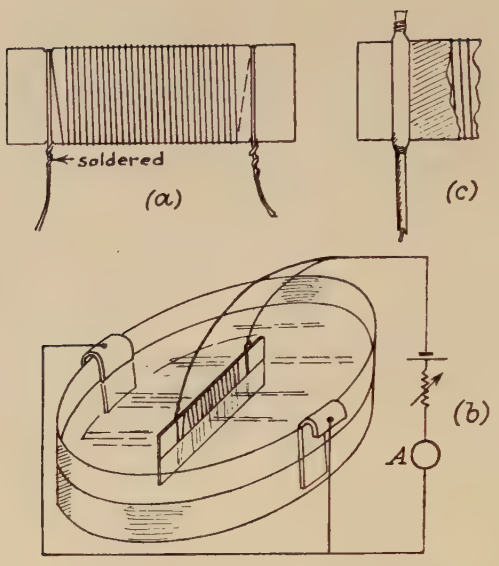

Figure 2. Construction of glass flux plate.
(a) Arrangement of constantan winding.
(b) Plating half the winding with copper.
(c) Attachment of polystyrene sleeving.

been done by side by side comparisons in the soil with a calibrated " bismuth-disc" flux plate. The calibration device described by Hatfield and Wilkins (1950), while employing similar principles to that described above, would have the advantage of being suitable for the calibration of either type of flux plate.

Installing the flux plates in bare soil presents no difficulties with either type. A thin covering of soil is sufficient to give the surface over the plate the same radiative characteristics as the surroundings. The flux plates soon bed down after rain and make good thermal contact with the soil. The smaller a flux plate can be made the better, as it will produce less disturbance to the moisture conditions in the soil. The glass flux plate is superior in this respect to the " bismuth disc " variety.

With grass surfaces it is necessary to bury the disc some 1·5 to 2·5 cm below the surface and in this case, for accurate work, it is necessary to allow for the heat accumulation or loss by the layer of soil and vegetation above the flux plate. With short surfaces this often amounts to 5 to 10 per cent. of the total heat flux into or out of the soil and can be allowed for approximately if the temperature at the mid point of the top layer is recorded. It has been found that the glass plates, inserted under a thin flap of turf (care being taken to bed the plates on a smooth surface of the underlying soil), soon settle down and have no discernible effect on the grass, once the roots have grown round the plate.

A useful feature of these simple flux plates is that several can be used in series to give a much better estimate of the mean flux of heat into the soil than is possible from measurements at only one point. This becomes a very important consideration when dealing with more heavily vegetated surfaces than short grass.

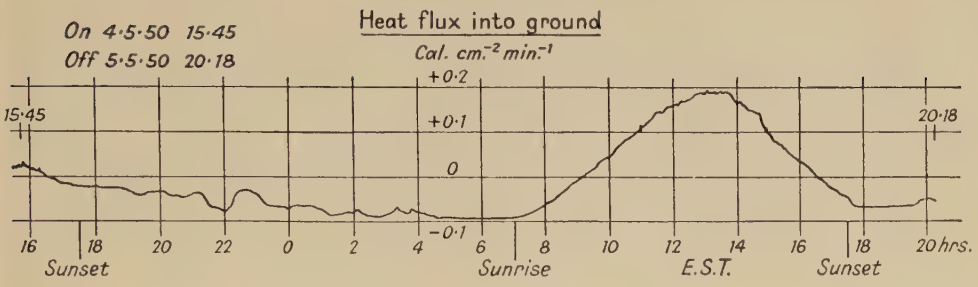

Figure 3. Record of heat flowing into the soil (grass surface) during clear weather.

A specimen record for a clear day is shown in Fig. 3. The glass flux plate was located at 1·5 cm depth below the surface of a meadow near Melbourne ; the grass, of somewhat sparse growth, being about 2-3 in. high, in general. Local noon was at 12.20 E.S.T.

Acknowledgments

The author wishes to thank Mr. R. J. Taylor for his ready co-operation in much of this work and for his suggestion of the use of a bismuth-copper combination for the heat flux disc. Mr. G. J. Vanderheiden made the requisite apparatus.

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Correspondence

Evidence for a world circulation

In the *Quarterly Journal* of October, 1949, Mr. A. W. Brewer in an interesting paper puts forward the idea of a world circulation in order to explain the observed dryness of the lower stratosphere. The argument is that there must be considerable turbulence in the stratosphere in order to maintain the observed uniform concentrations of carbon dioxide and of helium. This being so the temperature distribution can be explained by the effects of radiation, but the dryness of the stratosphere can only be maintained in the presence of this turbulence if the air is continuously being dried. Mr. Brewer then suggests a fairly vigorous world circulation as the mechanism by which this drying is effected. I wish to query the need for so vigorous a circulation and to raise one or two related points.

Whilst with the Meteorological Research Flight in 1943-45 Mr. Brewer seems to have made an unduly large proportion of his ascents on occasions on which there was a sharp fall of frost point on entering the stratosphere, and he has naturally concluded that this is a common event. The Meteorological Research Flight has now made a very large number of stratosphere ascents and we find that on the average there is little difference between the frost point lapse rates above and below the tropopause. This has been pointed out recently by R. Frith (1949) and is also clear from published diagrams due to the writer (1949). We also find that on the average the lower stratosphere is moister than Mr. Brewer's results suggest.

The more extensive data now available affect significantly the results of some of Mr. Brewer's calculations. For example :

1. We find that in the lowest 1 km of the stratosphere the humidity mixing ratio falls through a ratio of $3\frac{1}{2} : 1$, not $10 : 1$.
2. The mean frost point observed at the summit of those ascents which penetrated more than 1 km into the stratosphere is 196°A, and not 194°A. The mean frost point at the tropopause is 212°A, not 215°A, and the ratio between the corresponding humidity mixing ratios at the tropopause and the summits of the ascents is about $7 : 1$, not $20 : 1$.
3. The height Z' at which the water content has fallen to $1/10$ of its value at the tropopause is about 2 km, not 1 km. Thus to maintain the observed dryness of the stratosphere by motions parallel to the tropopause would require the air to be returned to the equator every 40 or 80 days only, corresponding to advection speeds of 3 or 5 km/hr, instead of 10 or 20 km/hr.
4. In section (5), putting in a value of w/K corresponding to our mean frost point curve gives $w = 15$ or 30 m/day instead of 25 or 50 m/day. Using these values in section 6 we find the average time taken by the air to move from the equatorial to temperate latitudes to be of the order 200 or 400 days, instead of 100 or 200 days. Taken in conjunction with 3 above this means that the effect of the advection alone is about $1/5$ of and not $1/10$ of the effect of the sinking.

The fact that the lapse rate of frost point is about the same above as it is below the tropopause is interesting and suggests that turbulence exists in the lower stratosphere which is of about the same order as that occurring in the upper tropo-

sphere. In his Section 5 Mr. Brewer says that the descent of air in his proposed circulation will " confine the transition from the moist air of the troposphere to the dry air of the stratosphere into a shallow layer just above the tropopause." I am not sure whether his theory demands such a layer but if so it must be wrong. In this case, and in view of 3 above, it may be that the actual circulation is one in which advection rather than sinking plays the main part. This advection need not be parallel to the tropopause (for the tropopause does not vary continuously in height from equator to pole and will usually be double in some regions), and may be from the upper equatorial troposphere to the lower temperate stratosphere.

H. C. Shellard

Meteorological Research Flight,
Royal Aircraft Establishment,
Farnborough, Hants.
2 January 1950.

References

Frith, R. 1949 *Weather*, London, **4**, p. 330.
Shellard, H. C. 1949 *M.R.P.* 486, London, Met. Off.
1949 *Met. Mag.*, London, **78**, p. 341.

Reply

I am very glad that Mr. Shellard has raised the question of the effects which more recent data have upon the argument of my paper. His results were not available to me at the time of writing the paper.

I entirely agree that a reduction of the rate of fall of humidity mixing ratio in the lower stratosphere by about 3 : 1 makes it just possible to explain the results without any steady mean circulation, as was suggested to be necessary in my paper. Mr. Shellard's points 1-4 are very real and show how much we need evidence on all these questions.

I do not however agree that there is any connection between the lapse rate of frost point in the stratosphere and in the troposphere. Up and down movements which unquestionably occur on a large scale in the troposphere (from dynamic causes, not the trivial movements of turbulence) will account for the observed lapse rates of frost point and temperature in the troposphere, but no similar explanation can be given for the observed lapse rate of frost point in the lower stratosphere as upward movements without falling temperature will not dry air, but if occurring in these latitudes would only carry moist air into the stratosphere.

It is very easy to mislead one's self by presenting the observed data in some particular way. In Fig. 1 I reproduce Fig. 3 of Mr. Shellard's paper M.R.P. 486 (Revised), and it will be seen how the frost point curve appears to run through the tropopause without much apparent change of slope. If however the curve is measured it will be found that in 25 mb below the tropopause the frost point falls 7·2°F but in the 25 mb above the tropopause the frost point falls 11·8°F. Thus this slight kink actually corresponds to a 65 per cent. increase in lapse rate. In

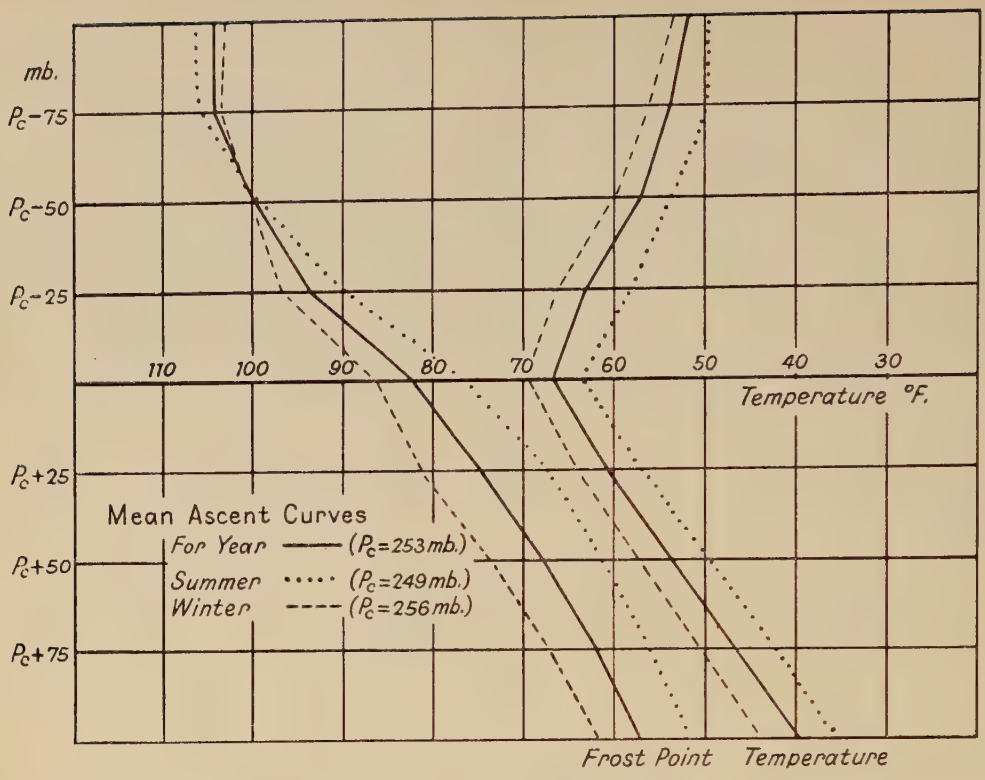

Figure 1. Mean ascent curves of frost point and air temperature (negative temperatures along abscissa.)

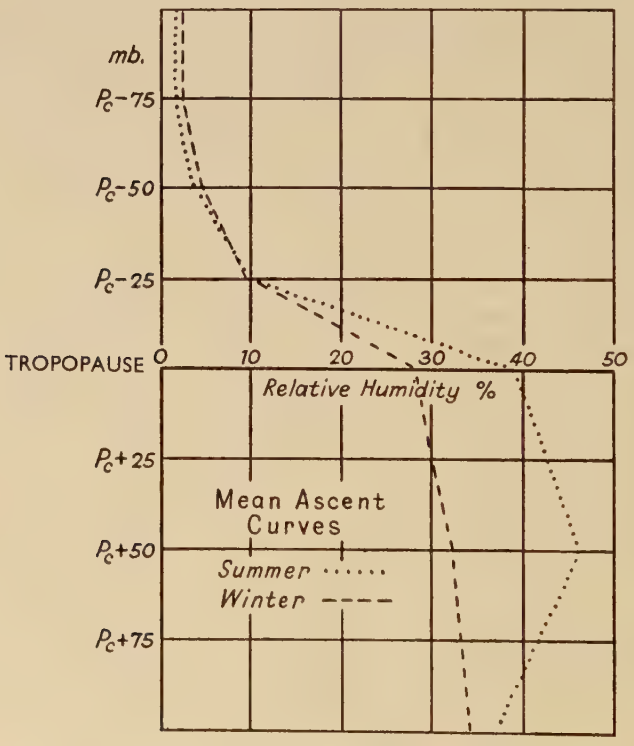

Figure 2. Mean ascent curves of relative humidity.

Fig. 2 the water content is plotted as relative humidity and this particularly shows what I mean when I state that the transition from the moist air of the troposphere to the dry air of the stratosphere is confined to a shallow layer. This diagram is probably about as misleading in one direction as Dr. Frith's note (*Weather*, October 1949) is in the other direction ; in Dr. Frith's diagram levels are averaged with respect to height above the ground rather than height above the tropopause which is the reference level in this case.

With regard to Mr. Shellard's last sentence it is clear that the air one or two km above the tropopause with a relative humidity of only 2-4 per cent. must have subsided considerably from the region where its frost point was reduced as low as —105°F, or it must have been warmed by radiation, as otherwise it would not have the very low relative humidity which it is observed to have. Its frost point is so low that it must have been dried very near to the tropopause at the equator and about 4-6 km above its present level.

A. W. Brewer

The Clarendon Laboratory,
Oxford.
23 February 1950.

Summer weather of the Sudan

The location of the Intertropical Convergence Zone (I.C.Z.) as shown in Fig. 1 of El-Fandy's paper " Summer Weather of the Sudan " (*Quarterly Journal*, **75**, p. 375, 1949) is not correct ; moreover the terms I.C.Z. cannot be applied in the Sudan for the following reasons :—

(a) The I.C.Z. which El-Fandy assumes to separate the hot northerly winds from the cool SW monsoon of his Fig. 2 cannot be quasi-stationary when drawn across the isobars as in his Fig. 1 ; and the hot northerly winds of Upper Egypt will turn round the centre L_1 and flow over N. Sudan as *hot* SW winds forming the core of that low, a fact which is observed in daily analysis of synoptic charts in summer.
These hot SW winds are separated from the cool and moist SW monsoon by a frontal zone (or a zone of separation) which is of a quasi-stationary nature and lies nearly parallel to the isobars at about Lat. 16°N. El-Fandy's Fig. 19 can be taken as an example to illustrate the above views where the northern part of the SW current is seen to be of the same temperature as the N winds over Upper Egypt, and distinctly warmer than the homogeneous *cool* SW winds over central Sudan. Thus, the zone of separation between the hot SW winds of the northern Sudan and cool SW monsoon should be located some 400 km. south of that shown in Fig. 19 (thunderstorms will still be in the cool SW monsoon).

(b) The I.C.Z. is defined as the narrow zone where NE and SE trades meet with *marked convergence* ; and it is seen that the hot Northerly Current of the N hemisphere turns to SW and flows beside the SW monsoon with no marked convergence ; therefore the name I.C.Z. is here not justified and I.F.Z. (Intertropical Frontal Zone) is proposed in place of the I.C.Z. when it enters the heated land mass of Africa and Asia, as being the northern limit of the cool SW monsoon originating as SE trades.

The use of pilot balloon observations *alone* in drawing the lines of flow may lead to errors when an air stream bends or meets another stream. Such errors are met with in El-Fandy's paper. If we look, for example, at his Fig. 14, we see that the SW winds over N. Sudan were all assumed to originate as SW monsoon, whereas in fact the northern part originates as hot NE winds and turns round the Sudan low to SW as explained above. This will be clearer when the isobars and air temperature are inserted for that day as shown in Figs. 1 and 2 of this note.

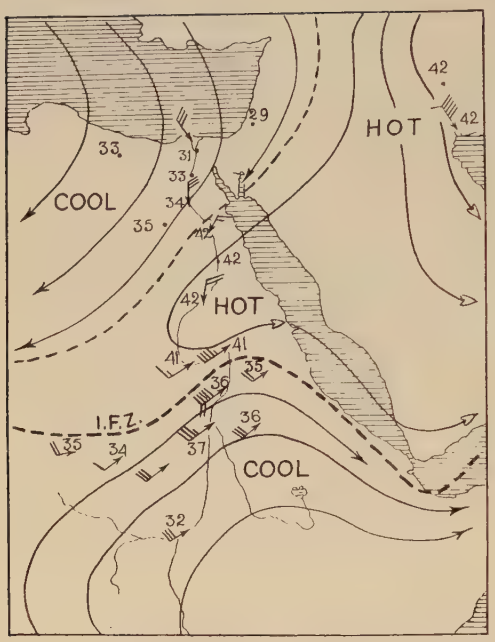

Figure 1. Suggested modification of El-Fandy's Fig. 14. Surface temperatures are inserted to support the modification.

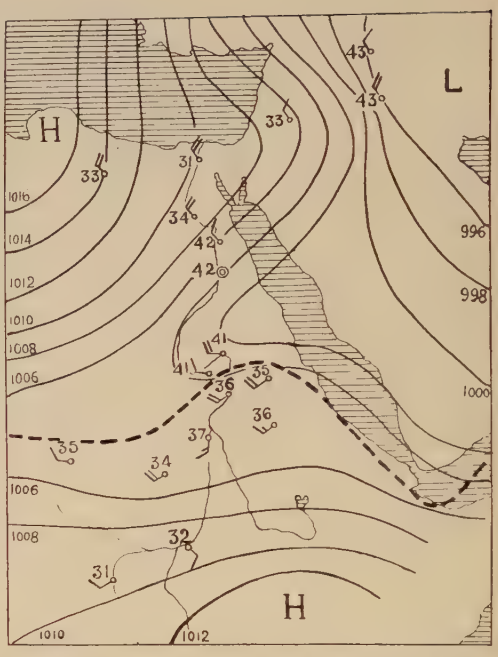

Figure 2. Surface chart at 1200 G.M.T. on 11 July 1943 supporting the suggested modification.

We infer that the analysis, location of the frontal zone, and lines of air flow in El-Fandy's paper need amendment which should be taken into account before his conclusions can be accepted.

K. H. Soliman

Meteorological Dept., Cairo,
20 January 1950.

Reply

The I.C.Z. is not stationary, but oscillates north and south. Figs. 1 and 2 of my paper give its average position, being the boundary between the dry northerlies and the moist southerlies. Weather disturbances occur within the southerlies, usually hundreds of miles south from this boundary. What is observed is that the hot northerlies may be mixed with the southerlies and appear as hot SW surface winds over the N. Sudan. This is made clear in the discussion of " Continental Tropical Air " (p. 380) and an illustration is given in Fig. 17 by the belt A B C D. Mr. Soliman is unfortunate in referring to Fig. 19 as sand-storms and thundery cloud or rain can only occur within the SW monsoon in this season. Attention should be directed to atmospheric features and elements which are more significant than surface temperatures. The latter are frequently misleading.

Fig. 1 given by Mr. Soliman is a surface map with surface temperatures, while my Fig. 14 is the flow at 1000m and I see no meaning in the argument, particularly on referring to my Fig. 12 which gives the lines of flow at 4000m on the same occasion. Figs. 14 and 12, together with the argument given in the paper (p. 387), show clearly that the N. Sudan is invaded by solid strong southerlies.

Mr. Soliman's discussion is restricted to the definition or location of the I.C.Z., and his argument is based upon some surface temperatures over the N. Sudan, which is an area of almost cloudless skies and intense insolation. The I.C.Z. does not play any active part in the weather deteriorations. Even if it is not drawn at all this will not alter in any way the conclusions and results summarised in the opening of my paper. It remains to be stated that Mr. Soliman repeats the term " fact " and the expression " not correct " in his discussion, but he then fails to give any acceptable proof of upper air flow.

The idea that on the average the northerlies turn into SW currents, as Mr. Soliman suggests, is not correct. Over S. Egypt and the N. Sudan the northerlies are normally NE trades. This is made clear throughout my paper, notably by Fig. 2 where actual averages are given. In the special conditions of the passage, over Egypt, of troughs in the upper westerlies developments of cyclones in the upper air may ultimately occur over the Nile Valley in the manner described by me in a new paper " Troughs in the Upper Westerlies . . . .," which has been recently accepted for publication in the *Quarterly Journal.** Only under such conditions may the northerlies turn into southerlies, but these deviations from the normal must not be confused with average conditions, as by Mr. Soliman.

M. G. El-Fandy

Farouk I University,
17 March 1950.

Measurement and estimation of atmospheric radiation

I have read with great interest Dr. G. D. Robinson's (1947, 1950) papers entitled " Notes on the measurement and estimation of atmospheric radiation." Dr. Robinson's work is a very welcome addition to the investigation of radiative flux in the atmosphere, and it is gratifying that such excellent empirical studies are being made.

Dr. Robinson found that values of sky radiation determined with the use of the Elsasser chart were generally higher than the measured values, the discrepancy decreasing and changing sign with increasing water vapour content or temperature. This discrepancy is especially serious because the total sky radiation should be the most accurate quantity determined from the Elsasser chart, for, as Dr. Robinson has pointed out, most of the sky radiation comes from the very lowest portion of the atmosphere under normal conditions of water vapour distribution. It is a question of considerable importance whether the errors resulting from the use of the Elsasser chart are due mostly to the approximations in the theoretical treatment (notably the neglect of the half-width of the lines in comparison with the line spacing in the derivation of the generalized absorption coefficient), or to erroneous values of the physical quantities used in the construction of the chart. The simplicity of the Elsasser chart makes it desirable that the latter possibility be examined before rejecting the method.

It occurred to me that a major part of the discrepancy might be explained by the large value of the half-width used in Elsasser's calculations, *i.e.* 0.25 cm^{-1} (Elsasser 1942). Recent measurements with high resolution, both in the infra-red (Adel 1947) and microwave (Becker and Autler 1946) regions, result in values very close to 0.10 cm^{-1}. Since the half-width enters only as a direct factor into the path-length in the generalized absorption coefficient (Elsasser 1942, p. 39), a correction can be made by the simple procedure of multiplying the effective moisture by the factor 0.4. I have done this in the case for which Dr. Robinson (1947) gave data in Part 1, and found exact agreement with the measured value of sky radiation.

It would be of interest to see if this corrective factor would account for the discrepancies in the cases for which Dr. Robinson did not give meteorological data. The increase of

* Since published in **76**, p. 166, 1950. (Editor).

the discrepancy between the theoretical and empirical curves with decreasing water vapour content is what one would expect, since the effective height of the radiating layer is most sensitive to the value of the half-width for small water vapour content. The argument for this is as follows : in the wings of the absorption lines the absorption coefficient is roughly proportional to the line width. The radiation mean free path, therefore, is roughly inversely proportional to the line width. In other words, a given variation in the line width would change the mean free path by approximately the same *proportion* for all values of the line intensities and/or water vapour content. The *actual* change in the mean free path of radiation, and therefore of the effective temperature or height of sky radiation, will accordingly be the greatest for small water vapour content (*i.e.* large mean free path). The reverse effect, will, of course, occur near the line centre, but even for small line intensities and water vapour content the mean free path is extremely small and the first effect will not be compensated.

The increase of the discrepancy with decreasing temperature is also to be expected since water vapour content and temperature are positively correlated for large-scale atmospheric fluctuations.

Lewis D. Kaplan

Meteorologist, United States Weather Bureau,
University of Chicago,
14 June 1950.

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Adel, A.	1947	*Phys. Rev.*, Lancaster, Pa., **71**, p. 816.
Becker, C. D. and Autler, S. H.	1946	*Ibid.*, **70**, p. 300.
Elsasser, W. M.	1942	*Harvard Met. Studies*, Milton, Mass., No. 6.
Robinson, G. D.	1947	*Quart. J. R. Met. Soc.*, London, **73**, p. 127.
	1950	*Ibid.*, **76**, p. 37.

Reply

I am glad to learn from Mr. Kaplan's letter that my measurements of total incoming radiation are proving of more than local interest. Following his suggestion I used the method he advocates to compute the incoming radiation for 1 March 1947, 0100 G.M.T. The results, to which I have added Mr. Kaplan's for 5 September 1946, 2100 G.M.T., are :—

Date	Incoming Radiation (mw cm^{-2})			
	Observed	Revised Kew Chart	Elsasser Chart	Kaplan
5 Sept. 1946	29.4	29.4	30.9	29.4
1 March 1947	19.6	20.2	22.2	20.5

In Fig. 1 I have plotted the emissivity of water vapour in the presence of CO_2 ($E(u)$) against the path length u ; the dashed line being the original Elsasser values for $+10°C$, the full line the revised Kew values, the circles and crosses Mr. Kaplan's modification of Elsasser's values for $+10°C$ and $-10°C$ respectively. The discrepancy between the computations and observations at small path lengths and low temperatures remains and I have given reasons for suggesting that it cannot be removed by adjusting the $E - u$ relation at a given temperature without conflicting with experimentally determined emissivities (Robinson 1950, Section 4.).

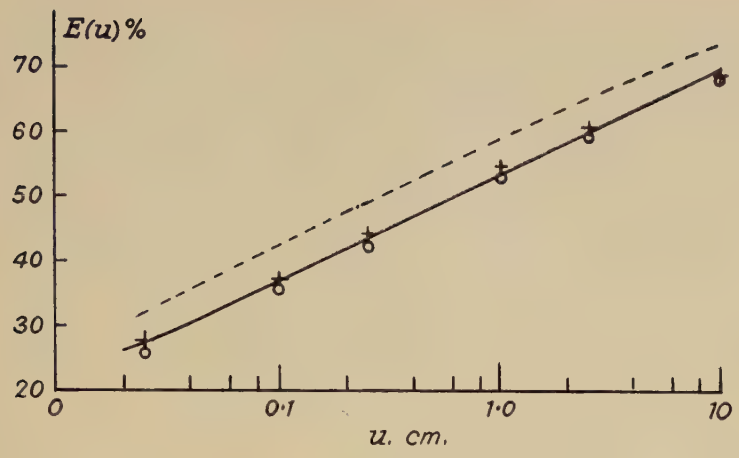

Figure 1. Emissivity $E(u)$ of water vapour (in the presence of CO_2) versus path length (u) of precipitable water.

One aspect of the correction which Mr. Kaplan proposes appears curious to me. As I understand Elsasser's work, the computations of absorption coefficient which employed the half-width 0.25 cm were limited to the rotation band. For the 6μ band he employed absorption coefficients based on Fowle's observations. Mr. Kaplan's results therefore suggest that these observed coefficients are too high by much the same factor as the computed coefficients at longer wave lengths.

G. D. Robinson

Kew Observatory,
12 July 1950.

Reference

Robinson, G. D. 1950 *Quart. J. R. Met. Soc.*, London, **76**, p. 37.

The meridional transport of angular momentum in the atmosphere

In the issue of the *Quarterly Journal* dated April 1950, there appears an article entitled, "The intensity of the net meridional circulation," by H. Riehl and T. C. Yeh. The discussion touches upon the problem of the meridional transport of angular momentum in the atmosphere. Although it is to the credit of the authors that they approach the question through the use of observations, there are various considerations of importance which arise concerning their work and more specifically concerning their interpretation of the results, which appears to contain a basic error.

Setting aside all questions pertaining to the crudity of the data which they use, let it be assumed for argument's sake that the scheme of meridional circulations obtained by Riehl and Yeh is representative of global conditions. It is then necessary to examine

correctly their significance for the meridional transport of angular momentum. In the mean this northward transport should attain a maximum at the latitude which separates the surface easterlies in the subtropics from the surface westerlies farther north. The magnitude of this transport may be estimated from the surface torques of the westerlies (and polar easterlies farther to the north). Such estimates were made by White (1949) and by Widger (1949) for the month of January 1946. The value obtained was about 30×10^{25} cgs units/sec for the hemisphere. The same investigators have since obtained a value of about 20×10^{25} cgs units/sec from normal maps for January. These figures include the torques due to pressure differences across mountain ranges. It has been suggested to the writer that the methods used for measuring this component may give a significant *underestimate* of the total.

In order that a meridional cell should carry angular momentum northward, the northward-moving branch must carry more of such momentum than the southward-moving branch so that the net effect is due to the difference of the momenta of the two branches in view of the fact that the cell in the mean accomplishes no net meridional mass transfer. It therefore follows that only the momenta relative to the earth need be considered, as stated by the writer on several previous occasions. Let it be assumed with Riehl and Yeh that the net southward velocity at latitude 30-35°N decreases linearly from 1 m sec^{-1} at sea level to zero at 1 km. Since this kilometre represents about 100 mb in pressure, it follows that the return flow above must be equivalent to a flow of 1 m sec^{-1} through a depth of 50 mb, on mass continuity principles.

Computations based upon normal sea level and upper air maps indicate that the normal geostrophic westerly wind at latitude 30-35°N in January increases approximately linearly from zero at sea level to 35 m sec^{-1} at the mean height of the tropopause near 12 km. Therefore the relative momentum of the upper layer is probably not underestimated by ascribing to it a mean eastward speed of 20 m sec^{-1}. A simple computation shows that the net transport of angular momentum due to the cell is about 1.8×10^{25} cgs units/sec for the entire latitude circle. It is seen therefore that, in view of the figures given previously, most of the needed transport must be accomplished by other means, and an eddy transport is the only actual alternative. Thus if it were definitely known that the circumstances are as indicated, we should have in our possession, through this means alone, a well-nigh sufficient demonstration that eddy processes accomplish nearly all of the meridional transport of angular momentum from the tropics to the zone of surface westerlies. An independent appraisal of the effectiveness of meridional circulations of the present type has been made previously by Mintz (1949) with results similar to those obtained here.

The source of the error in the conclusions reached by Riehl and Yeh is moreover not difficult to see. In simplest terms it may be stated as follows. The estimate of 6 cm sec^{-1} for the speed of the northward branch obtained by Palmén in order that it should carry a typical amount of (absolute) angular momentum includes the angular momentum due to the earth's rotation. However if this angular momentum is included in the northward branch, it should also be included in the southward branch whereupon in the net its contribution is cancelled, because no net mass transport takes place across the latitude circle.

Victor P. Starr

Massachussets Institute of Technology,
16 June 1950.

References

Mintz, Y. 1949 *The maintenance of the mean zonal motion of the atmosphere.* Doctoral dissertation, University of California, Los Angeles.

White, R. M. 1949 *J. Met.*, Lancaster, Pa., **6**, p. 353.

Widger, W. K. 1949 *Ibid.*, **6**, p. 291.

Reply

Our paper was concerned with momentum transfer only in a secondary way, namely to see whether Palmén's (1949) discussion was based on a reasonable estimate of the intensity of the net meridional circulation or not. It turned out that his values were reasonable. Since Prof. Starr, however, raises the whole problem of momentum transfer with us, the following will show our specific objection to his approach, in concurrence with Palmén.

It is debatable whether the mean meridional circulation is as negligible a factor for the net momentum transfer across latitude 35° as stated. If the minimum circulation assumed by us transfers about 10 per cent of the momentum lost to the ground by friction north of 35°, the contribution would rise to a large fraction of the total if the true meridional circulation is several times larger. This point cannot be settled. The evident importance of the meridional circulation, however, lies in the following. As stated by Prof. Starr (1949) himself: " . . . . mean meridional circulations when present can have a profound influence upon the vertical distribution of the meridional transport of absolute angular momentum in the atmosphere". This influence stems from the term $\int_0^{2\pi} R^3 \cos^3\phi \; \omega\rho \; \delta v \, d\lambda$ in the momentum transfer equation (cf. Palmén), where R is the radius of the earth, ω its angular velocity, ρ the density, δv the mean meridional circulation, ϕ the latitude and λ the longitude. When calculated with the data of our articles for January in the northern hemisphere, the term has the value of 24×10^{25} cgs units/sec at latitude 35° in each of the two vertical layers. It is just as large as the total loss due to surface friction north of 35° as computed by Prof. Starr's students. The term quoted vanishes when integrated vertically over the whole atmosphere in any latitude belt, except in the case of net mass flux. *But within each branch of the meridional circulation its contribution can equal or exceed that due to eddy transfer. Therefore a very strong vertical momentum exchange must exist and the direction of transfer is downward*, especially south of the subtropical ridge where both $\cos\phi$ and δv are large. It is mainly in this major aspect that we differ from Starr (1949) and Widger (1949) who show an upward flux in this region, against the gradient.

The following will illustrate our point further. We compute the term mentioned above to be 138 units at latitude 20°, 84 at 25° and 24 at 35° (all values in 10^{25} cgs units/sec). Therefore the accumulation (depletion) due to this term in each of our two vertical layers is 54 units between latitudes 20-25° and 60 units in the interval 25-35°. After allowance for continuity using Widger's data, the resulting *downward* transfer through the boundary separating the northward and southward branch of the meridional circulation is 49 units between latitudes 20-25°, and 58 units between latitudes 25-35°. These values are subject to slight changes, depending on continuity requirements above 7.5 km where Widger had no observations. In contrast to these values, Widger has computed an *upward* transfer through the 1.5 km surface of 9 units between latitudes 20-25° and 6 units between latitudes 25-35°.

This shows clearly that the existence of even a weak meridional circulation has an enormous influence on the vertical distribution of the momentum balance in any layer. It is evident that the momentum transport diagrams presented by Starr (1949) and Widger (1949) will undergo profound alterations if allowance is made for the meridional circulation. Further calculations demonstrating the role of the vertical momentum exchange as a major brake on the easterlies in the trade wind belt will be offered by us in another paper to appear shortly. Under the circumstances, it is difficult to agree with Starr (1949), at least for the lower latitudes, when he states that " (meridional) circulations . . . . are at most of secondary importance as compared to horizontal exchange processes which then appear to be the dominant factor in the general circulation".

H. Riehl and T. C. Yeh

University of Chicago,
24 July 1950.

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Palmén, E.	1949	*J. Met.*, Lancaster, Pa., **6**, pp. 429-430.
Starr, V. P.	1949	*A physical characterization of the general circulation*, Cambridge, Mass., Dep. Meteor. Mass. Inst. of Tech., Gen. Circ. Project Rep. No. 1.
Widger, W. K., Jr.	1949	*J. Met.*, Lancaster, Pa., **6**, pp. 291-299.

A note on nocturnal cooling

In " A Note on Nocturnal Cooling " (*Quart. J. R. Met. Soc.*, 1950, **76**, p. 173) I gave a formula for the fall in temperature at the ground during nocturnal cooling. In that note the nocturnal radiation, R_N, was taken as a constant. If R_N is variable in time, say $R_N = R(t)$, it follows immediately from Eqn. (24) that the solution is

$$T_g = -\frac{1}{\lambda \rho_1 c_1 K_1^{1/2}} \left(R(o) f(t) + \int_0^t f(t-\tau)\, dR(\tau) \right) \quad . \quad . \quad . \quad (1)$$

$$\text{where } f(t) = \frac{t^{1/4}}{\Gamma(5/4)} - \frac{1}{\lambda} + \frac{2\sqrt{2}}{\pi} \int_0^\infty \frac{\exp(-u^4 t)}{u^2 + \sqrt{2}\, u\lambda + \lambda^2}\, du$$

For reasons given in section 6 of the note I do not think that formula (1) has much practical value ; nevertheless from a theoretical point of view formula (1) makes the solution more complete and also indicates the correction to be made to account for the variation in R_N from its assumed constant value $R(o)$.

E. Knighting

Meteorological Office, London
13 June 1950

Reviews

Rainfall and Runoff. By E. E. Foster. New York (Macmillan), 1948. 8vo. Pp. 487 + xix ; 179 figures. £3. 7*s*. 6*d*.

Hydrology. By C. O. Wisler and E. F. Brater. New York (John Wiley), 1949. 8vo. Pp. 419 + xi ; 131 figures. 48*s*.

The author of the first of these books has applied statistical methods to American rainfall and runoff data and presented the results in 92 tables and 179 diagrams. He appears to believe that if the data can be forced to fit a statistical relationship derived in some other field for some other purpose, then that relationship is a theoretical relationship for his data. There is a little formal mathematics in the text, unbelievably inaccurate in places (*e.g.* pp. 163 and 248), but as no use is ever made of it the reader is merely irritated without being misled. The collected data will be useful for reference, but apart from this the book will appeal only to other amateur statisticians who find pleasure in mishandling the finely-wrought tools provided by professional mathematicians.

Wisler and Brater cover much the same ground as Foster and with the same limitation of drawing almost exclusively on American sources of material and reference, but with the important difference that they have provided a well written textbook suitable for students and helpful for experts. In their survey of meteorology they have sensibly drawn at some length on Petterssen's books ; in the survey of ground water they have had a chapter specially written for them by J. G. Ferris of the U.S. Geological Survey, a very good chapter that fits in without any major clash either in style or depth of treatment.

The first part of the book sets out general principles, working back from the stream to the source of its water, *i.e.* through chapters on the hydrograph, the watershed, and precipitation. British readers may be surprised to find illustrative examples based on maintained rainfall rates of 4 in./hr ; as winter flooding of some of our own rivers will occur when about 2 inches of rain fall in a fortnight these examples must be studied closely to pick out what is generally useful from special cases. There are a few minor blemishes in the chapter on the effect of watershed characteristics on runoff : *e.g.* half-a-page is taken to work out the relation between the circumference and area of a circle ; the term " hypsometric " is introduced without definition, but it has nothing to do with the hypsometer familiar to physicists ; two conventions are used simultaneously in a section on " order " of streams ; and, finally, the probable effect of lowering a water table by field drainage is stated to be a decrease in transpiration, whereas there is good reason to believe exactly the opposite is true. Precipitation is introduced through atmospheric humidity and then there are discussed sources of rain, meteorology of rainfall, rain and snow gauging, estimation of means in space and time, and the relation between storm frequency and mean annual rainfall. Frequency is defined as the average time between falls — an unnecessary confusion between *frequency* and *period* of recurrent events. Duration — Area — Intensity — Frequency relationships are discussed at length, illustrated by some crowded diagrams, showing curves for several hundred American storms.

In these short-period phenomena of rain storms and snow-melt, evaporation can usually be neglected, but in the study of long-period changes the sources and causes of water loss must be considered. Of these evaporation is much more important than interception and leakage and there is a well balanced survey (within American literature) of evaporation, prominence being given to the fine work of Rohwer at Fort Collins. Arising out of this is a discussion of transpiration which includes a most welcome diagram showing a diurnal cycle in stream flow imposed by the diurnal cycle of transpiration of vegetation growing near it, but the soil physics and biology have been taken from rather antiquated sources, for there are few who would agree that for any particular type of vegetation the rate of transpiration varies with growth rate. Evaporation cannot be estimated as the product of crop yield and a *transpiration ratio*. Nor is it generally true to say that annual evaporation from bare soil is one half annual rainfall ; in the few places where direct measurements have been made it is so, but reason and evidence combine to show that is not true either in arid or very humid areas. The importance of changes in ground storage is rightly stressed in the discussion of total water losses, but is overemphasized in a numerical example in which pore space and specific yield are confused at 33⅓ per cent. (about 1 per cent. in some chalk formations, in most aquifiers the specific yield is only a few per cent.).

The response of a stream to rainfall depends very much on the rate at which the soil can absorb rainfall — its " infiltration capacity " (*capacity* is much better reserved for a quantity rather than a rate). The subject is difficult, but an important chapter shows what a promising start has been made on its study. In this and other problems of soil physics the authors should discard the outmoded idea that water in soil is held as films on the particles ; the idea has never been useful and is physically unreasonable.

Ferris gives a self-contained account of the effects of geological and physical factors on ground water, and it is interesting to note that under some conditions well-level can fluctuate as a result of

changes in atmospheric pressure, tides and passing railway trains! Kelvin's method of images is applied to draw-down problems in aquifiers bounded by impermeable formations. Towards the end is a description of a successful attempt to recharge ground water resources by feeding in surplus river water. Although this is a very attractive simultaneous solution of two important problems in hydrology, the method cannot be used in Britain, and it is probably only of very limited use in America.

From the basic principles so outlined the authors turn to their use in practical problems :

(1) maximum flood flow to be expected ;
(2) minimum flow to be expected ;
and (3) monthly, annual and long-term flows.

Examples are worked out for small, medium and large watersheds, but because of their great economic importance floods are treated in greatest detail : causes, seasonal distribution, frequency, prediction and control. The complexities of flood control are clearly and dispassionately stated in a section that should be read by all laymen who think they know the answer.

A chapter on methods of stream-gauging brings to a close a book that can be recommended to all interested in the fate of rainfall.

H.L.P.

Einführung in die Grosswetterkunde. By FRANZ BAUR. Wiesbaden (Dietrich Verlag) 1947. 8vo. Pp. 165 + VIII ; 32 figures, 20 tables. 9 German marks.

Musterbeispiele europäischer Grosswetterlagen. By FRANZ BAUR. Wiesbaden (Dietrich Verlag) 1947. 8vo. Pp. 36 ; 25 figures, 2 tables. 4 German marks.

The author of these works will be known to many as the pioneer of medium and longer-range weather forecasting in Europe by scientifically reasoned methods. Only Russia (Multanovsky 1912) can claim to have begun a serious attack on the problem earlier. Baur's first writings were on mathematical geography and later from 1919-26, when he was in charge of the first bioclimatic station in Germany at St. Blasien in the Black Forest, on statistical studies of climatology and the general circulation of the atmosphere. In 1929 he became the first head of the research institute for long-range weather forecasts established by the Prussian ministry of agriculture. From 1932 onwards ten-day forecasts for Germany were issued during the summer ; those for the years 1933-36 were tested by Page and Clapp in U.S.A. (*M.W.R. Supplement* 1940, U.S. Weather Bureau, No. 39,) and, although the results for the second halves of the ten-day periods were not significantly better than chance, the first five days gave a 75 per cent. verification with respect to the elements of temperature, precipitation and sunshine.

This figure represents a forecast which must already have economic value and a result which still commands respect. The first edition of Baur's introduction to this research (*Einführung in die Grosswetterforschung*) appeared in 1937. The study of broad-scale synoptic relationships (*Grosswetterforschung*) and hemisphere or world-wide circulation patterns as they occur from day to day is still one of the least developed branches of meteorology. In fact its development is even to-day limited by the available chart material. Nevertheless a long list of papers published by Baur and his collaborators in the professional journals stands as witness to a steadily increasing body of knowledge. It may perhaps be considered a misfortune that Baur's research institute was dissolved in 1945.

Publication of a general account of Baur's methods and experience has long been promised ; and these two instalments, one of which is really a third and fuller edition of the original *Einführung*, will be welcomed by many readers both professional and lay ; for the work is so arranged as to meet the preferences of both. The shorter volume consists largely of a catalogue of the twenty-five *Grosswetterlagen* (broad-scale synoptic situations) now more or less standardized for type-classification of weather situations affecting Europe and the eastern North Atlantic. The reader's convenience would have been better served by including this material in the *Einführung* as a single book, but no doubt the author was anxious to secure earliest possible publication by the instalment method. Some investigators subdivide the *Grosswetterlagen* a little further, others for other purposes group them into half-a-dozen broad types ; but they are very widely used in one form or another and this index is a key to much of the German literature.

It is interesting to note that Baur's *Grosswetterlagen* were originally developed from Gold's twenty-eight synoptic types for NE. France and southern England (1920, *Geophys. Mem.* London, No. 16), amplified and extended to cover the area from Greenland to the Dardanelles and from the Azores to the White Sea and to take some account of associated upper air events. Baur and the other German investigators have also made acknowledgment to other British meteorologists of earlier generations, notably Buchan and Mossman, G. T. Walker and C. E. P. Brooks ; in latter years we seem to have let our attention be drawn away from this field.

Baur's correlation work is characterized by a strong search for the underlying physical explanations. Often these are presented in very simplified form, but the statistical results themselves once the necessary significance tests are satisfied enable Baur to assess how far the working of a given process is complicated in practice by the operation of other controls. The *Einführung* is divided into sections on the general circulation and the relation between broad-scale circulation patterns and spells of weather (based on a classification of daily surface weather maps since 1881) ; the heat and radiation budget of the atmosphere ; terrestrial influences affecting the atmospheric circulation — ocean currents, polar ice, *etc.*; cosmic (*i.e.* solar) influences and their probable working ; periodicities real and fallacious and deduced natural periods for the completion of certain processes ; and finally the forecasting technique. An appendix deals with the use and significance of statistics as a tool in the research.

One misses any mention of long waves in the upper westerlies, although Baur himself has written of the significance of the stratosphere for the *Grosswetter* situation (spell-type) and has drawn attention to the *Grundströmung* or basic steering current found throughout the upper half of the troposphere and lower stratosphere. The effect of the presence and location of stationary waves is hinted at in several places under vague allusions to unspecified influences not necessarily external to the atmosphere (*übergeordnete Einflüsse*), which may or may not favour a certain development. Coordination of these viewpoints must be attempted.

The actual medium-range forecast is the product of a synthesis (in reality a subjective, but experienced judgment) of the results indicated by various approaches ; extension of the short-range synoptic development, considerations of "*Grosswetter-synoptik*" (spell-patterns, action-centres and their behaviour), analogue method, atmospheric rhythms and periodicities, *etc.* Solar-constant effects are a matter for further research and liaison with the astronomers, in any case probably only of concern to the longer-range forecasts. One gathers that the weak links in the technique have proved to be :

(1) periodogram analysis : the periodicities even when real are always liable to be swamped by the incidence of some new event ;
(2) symmetry-point procedures, which also break down without warning.

Only a few of the interesting results of experience can be mentioned here. Baur believes, for instance, that 48 hours is the limit of the ordinary synoptic method. Five days is the mean duration of a single *Grosswetterlage*, and even the large-scale synoptic developments cannot be foreseen in terms of their dynamical development beyond that. Quite small features in the existing situation may build up to a great effect in five days. The analogue method is related to the singularity calendar, and no apparent analogies with a discrepancy of more than ten days (in some German offices *six* days) from the relevant date of the year are considered. The non-occurrence of certain singularities in any given year has been found a highly significant indicator for certain subsequent trends leading to forecasts of over 90 per cent reliability.

Two specially interesting features are :—

(1) A map (p. 108) of the correlation of the solar constant in the winter months with the contemporary pressure over the eastern North Atlantic and Europe, values reaching +0·6 near S.W. Ireland and —0·5 over Finland (based on only 19 years) ; and
(2) Tables giving a homogeneous series of monthly mean temperatures for central Europe 1761-1946 and precipitation abnormalities 1844-1943.

Here is much information which all interested in forecasting more than 48 hours ahead must be familiar with, and a field of discovery about which we will hope to hear more.

H.H.L.

Tables of scattering functions for spherical particles. Prepared under the supervision of Dr. A. N. Lowan, Nat. Bur. Stand., App. Maths. Series 4, United States Government Printing Office, Washington, 1948. 6mo. Pp. 119 + xiii. 45 cents.

Meteorologists are concerned with the scattering of electromagnetic radiation by matter over a wide range of particle diameter, from the molecule to the raindrop (in ratio $1 : 10^8$), for radiations from the ultra-violet to radio waves. An exact theory of the process was provided by Mie* in 1908, following the earlier work of Rayleigh who obtained the well known and mathematically rather simple solution for the special case of $r << \lambda$ (r = particle radius, λ = wavelength). Mie's general solution is, unfortunately, in the form of series which converge only slowly as soon as r becomes comparable with or greater than λ and, in consequence, rather few computed values of the scattering in this meteorologically interesting range have been available. Blumer† evaluated the scatter coefficient

* Mie, G., 1908, *Ann. Physik*, **25**, 377.
† Blumer, H., 1926, *Zeit. f. Physik*, **38**, 920, and other papers.

as a function of direction relative to the incident radiation for α ($= 2\pi r/\lambda$) up to 12 and Stratton and Houghton‡ the total scatter coefficient (for all directions) up to $\alpha = 15$, both for unabsorbing material of refractive index $m = 1{\cdot}33$, corresponding to water.

The tables now under notice are much more extensive. They provide values of all the scatter functions for α between 0·5 and 6 and m between 1·33 and 2·0, and of the total scatter coefficient for α between 0·5 and 12, all for non-absorbing materials. A further section tabulates the total extinction coefficient when the scattering material is also absorptive, with absorption coefficients up to 0·1, for α between 0·5 and 7. There is a final section providing the backward scatter coefficient for a dispersive material such as water in the radio microwave region, for α between 0·1 and 3 — this for the radar cloud reflection phenomenon.

We have then in these tables the wherewithal to compute the scattering of solar radiation in the ultra-violet for particle radii from $0{\cdot}03\mu$ to $0{\cdot}3\mu$, and in the infra-red for particle radii from $0{\cdot}3\mu$ to 3μ, that is mainly for such particles as constitute haze, for which there is a large "empirical" literature dealing with so-called atmospheric turbidity. The problem of transmission and reflection of solar radiation by cloud droplets, about which there are very few reliable observational data, is unfortunately hardly capable of being touched by this set of tables and so, welcome as they are to the meteorologist, computations of the Mie functions for higher values of α are needed to enable some of his main problems to be solved.

P.A.S.

Radiative transfer. By S. Chandrasekhar. London (Oxford University Press) 1950. 8vo. Pp. 393, 35 figures. 35*s*.

This is primarily a mathematician's book. It is based on a series of papers which were published by the author in the *Astrophysical Journal* between 1944 and 1948. The original aim of the series was simply to determine numerically the distribution, in frequency and direction, of the radiation leaving a star and, by a comparison with observation, to determine the characteristics of the outer layers of the star. As the work proceeded, however, elegant and powerful mathematical methods emerged, based on certain physical principles of invariance, and leading to non-linear integral equations. The present volume is mainly concerned with these methods.

Most of the volume deals with the scattering of radiation. This has been discussed in considerable detail, and meteorologists will find the results invaluable for the interpretation of sky radiation and its polarization. The absorption and emission of radiation is discussed in much less detail and then only for radiative equilibrium. Mathematically speaking, absorption and emission by a gray atmosphere in radiative equilibrium is equivalent to isotropic scattering, and this problem is discussed fully. The case when the absorption coefficient varies to a moderate extent with the frequency is treated approximately ; Chandrasekhar suggests that the case when the absorption coefficient varies strongly with the frequency can only be treated numerically. I feel, however, that meteorologists should consider seriously whether Chandrasekhar's methods cannot be modified to apply to such problems as that of radiative equilibrium in the stratosphere.

T.G.C.

Meteorology for seamen. By Cdr. C. R. Burgess. Glasgow (Brown, Son & Ferguson), 1950. 8vo. Pp. 252. 102 figures. 15*s*.

In the past books have been written about Marine Meteorology by seamen who knew little meteorology or by meteorologists who did not know the sea. Now at last a book, and a good one, has been written by a meteorologist who is also a seaman. Commander Burgess's *Meteorology for Seamen* is an excellent and new book. It tells seamen what they want and need to know, rather than confining its field to the sketchy meteorological nothings that antiquated examination syllabuses have, for decades past, forced on disinterested seamen.

The book is in four parts :

(1) Factors which go to make up the weather ; (2) The climates of the oceans ; (3) Weather forecasting ; (4) Observing and recording the weather.

Illustrations are profuse, and often striking. The writing is plain, straightforward and seamanlike. Commander Burgess is to be congratulated on having avoided the mysterious boffin language in which too many writers on weather are apt to hide their knowledge (and their ignorances) from their public (and from one another). In this book the use of the words *high* and *low* to replace the polysyllabic *anticyclone* and *depression* is a typical and commendable rationalization. One may appreciate Commander Burgess's embarassed use of the word *hydrometeor* which is, he says, "a term that would have been omitted if there were a more simple one with which to replace it."

‡ Stratton J. A. and Houghton, H. G., 1938, *Phys. Rev.*, **38**, 159.

The book collects many pieces of knowledge which have not previously been readily available, — or have been hidden by a too passionately mathematical exposition which failed to make relatively simple facts meet the eye. One may mention an excellent chapter on sea and swell, based on Commander Suthons's pioneer, if unpublicised work in the Royal Naval Meteorological Service. There are useful notes on currents, and the wind effect on them. Icebergs receive a clear and comprehensive discussion. Valuable information about coastal weather and fogs has been included and a useful summary of weather effects on radar is given.

The reviewer particularly enjoyed a good chapter entitled " Some meteorological, optical, and other phenomena." The chapter on the use of one's own observations is very good. The cloud photographs (mainly by Commander Trendell) are a new and outstanding feature. A pleasing use of a wide variety of American and British sources for diagrams and climatic maps has been used. Some may, however, regret the absence of Bergeron's masterly diagrams " Mittlere Verteilung der Luftstromungen über dem Stillen Ozean " (1930, *Met. Z.*, Braunschweig, **47**, 246-262) which far surpass the " Generalized pattern of primary air masses and fronts " given by Commander Burgess, from U.S. Naval sources. These last show an abysmal ignorance of Southern Hemisphere fronts.

The lack of information about the Southern Hemisphere is not confined to the diagrams. The text does little more, in the naval phrase, than show the flag in the southern and maritime hemisphere. The publications of the last ten years on New Zealand, South African and South American meteorology surely provide a working basis for an introduction to Southern Hemisphere weather.

In the section on forecasting a most important general point is made that the best synoptic analysis is made by the good man with full facilities — the one at a weather central — and that the man at sea (like the man at a subsidiary land station) does best to take the broadcast analysis and forecast on it with his own observations. Time does not permit the seamen to make the analysis — the forecast is his job. Synoptic forecasters are always apt to be dazzled by their own powers of analysis and leave too little time for the actual forecast. The reviewer has a suspicion that this weakness is present in this section of the book. There is an adequate treatment of drawing up the broadcast analysis, but possibly too few examples of specific forecasts for ships in particular places on the globe. Not a single example of how a forecast is put into words could be found. And the words in a forecast are quite important unless it is made exclusively for the forecaster's own use. These difficulties of expression are exemplified by the difference in " Weather Shipping " forecasts as made by different organisations. Before the end of the war the forecasters were attempting a degree of precision of language by means of the introduction of ranges into the forecast. Now a change of style has been made and the forecasts have assumed the suave and practised ambiguity of landsmen telling fish stories in a Hull hostelry. Should one forecast " force 3-5 ? Is this too wide a mesh ? Should one choose between 3-4 and 4-5 ? Or should one throw up one's hand and call it " moderate to fresh " ? These are serious questions for a marine forecaster (as for any other) and are worthy of some discussion in a book of this calibre.

There are three other small points that might be mentioned in passing. The fact that it is impossible to measure visibility at sea is not mentioned. Without trespassing too far into seamanship and navigation it might have been possible to mention just how the wind and sea affect a ship's position. Some of the effects of weather on cargo are known and are worth mentioning.

But complaints about omissions are churlish in a pioneer volume in which so many good things are collected. Mariners everywhere will welcome an extremely useful addition to their highly selective bookshelves.

G.L.H.

Earth waves. By L. Don Leet. Harvard Monographs in Applied Science No. 2, Harvard University Press. New York (John Wiley), 1950. 8vo. Pp. 122. 58 figures and diagrams. 24*s*.

The Harvard Monographs in Applied Science provide a medium for publishing the results of research to a wider audience than that reached by individual professional journals. They are devoted primarily to the physical sciences.

This book presents a compact summary of present knowledge about waves in the earth and its applications to prospecting for minerals, determination of effects upon buildings, studies of weather, and the mapping of the broad earth structures of geological interest. It is divided into four chapters, the first three dealing with the measurement, observed types and transmission of earth waves, and the fourth with microseisms.

The main meteorological interest is contained in Chapter IV. The chief sources of microseisms around North America are examined with, in many cases, more elaborate equipment than was available in earlier work. It is confirmed that the disturbances are earth waves originating from storm centres over the oceans and not from the shallow seas, but the fundamental problem of how the waves originate under deep water has still not been solved.

This book contains a surprising amount of information for a single small volume and can be recommended. The price however seems somewhat on the high side.

A.W.L.

Das Klima der Vorzeit. Eine Einführung in die Paläoklimatologie. By MARTIN SCHWARZBACH. Stuttgart (Ferdinand Enke) 1950. 8vo. Pp. 211 + VIII. 70 figures, (No price given).

The study of past climates continues to develop in many directions, but the most solid advances of recent years are in the collection and interpretation of facts. In estimating the temperature and, in some cases the rainfall, of former geological periods from fossil plants and animals, for example, the pioneers relied mainly on the present habitats of their nearest living representatives — evidence which becomes more and more uncertain with increasing antiquity. The modern palaeoclimatologist, while not ignoring such evidence, relies rather on the physiological characteristics of the fossils and the chemical and lithological character of the rocks themselves. To take just two examples : the central nerves of leaves increase in size with increasing aridity of climate, and the secretion of lime by organisms and still more its chemical deposition are favoured by warm water. Prof. Schwarzbach's excellent " Introduction to palaeoclimatology," after two short introductory chapters on historical development and present-day climates, sets out these methods of reconstruction of past climates clearly and in detail, dealing successively with the evidence for warmth and cold, drought and heavy rain, wind, thunder, seasons and climatic cycles, and even upper winds.

A short chapter on geological time shows that some inconsistencies still remain between the accepted dating by the products of radio-activity and the direct counts of annual layers. This point is important because any demonstration of astronomical effects on climate must rest ultimately on accurate dating. Then follows a long and detailed account of the climatic history of the earth by geological periods, which will be especially valuable for future theories of the causes of climatic change.

The need for such an accurate basis of fact is very evident from the next chapter, in which the author sets out and briefly discusses the bewildering variety of such theories, most of which (26 out of 50) were propounded between 1890 and 1910. As knowledge grew, theorising declined — or is the supply of conceivable theories running out ? The honours of space are shared by the geographical theory (which however he criticises rather severely) and that of periodic changes of the elements of the earth's orbit (" radiation curve "). For the Permo-Carboniferous glaciation he regards some form of pole movements — not necessarily so extensive as Wegener's — as the only possible explanation. This chapter also forms an excellent summary, but the author appears to be less completely at home in meteorology than in geology. For example he states categorically that ocean currents cannot change the general heat economy of the earth and therefore it is doubtful whether simultaneous warming of both poles is possible. The whole chapter is written in a cautious vein, but he reaches the tentative conclusion that in the Mesozoic and Tertiary periods at least two main factors have predominated variations of solar radiation and the changing face of the earth.

The book is excellently produced, with numerous clear illustrations and maps. The list of references includes more than 850 items (without titles) ; there is a satisfactory index.

C.E.P.B.

Climatology. By A. AUSTIN MILLER. London (Methuen) 1950. (Seventh Edition). 8vo. Pp. 325 + IX ; 82 maps and diagrams. 18*s*.

Professor Austin Miller first produced his *Climatology* in 1931. In 1943 the third edition attempted to introduce the ideas of air masses in a new chapter, but apart from this the seventh edition differs little from the first beyond some additions to the list of suggestions for further reading. Even so the second edition of Brooks's *Climate through the ages* has as yet found no place, perhaps through the lag in printing time.

Twenty years is a long time for a meteorological textbook to remain virtually unaltered, and indeed the chapter on air masses is unsatisfactory and alien to the rest of the book because instinctively one feels that in the general classification too little attention is given to the vertical structure of the air, and, for that matter, to the concept of physical processes in the atmosphere.

That this is so is no stricture on Professor Miller who in this book has set out very clearly, as a textbook, the main facts as at present known of the climatology of the normal. Rather is it a stricture on the meteorologist in general, who has allowed the delineation of the normals of pressure, temperature and rainfall, together with the statement of the extremes, to pass as the expression of climate, whereas if the meteorologist pauses for one moment he must realise that climate is an agglomeration of a whole gamut of weather experiences, less easy to express in neat maps and tables than are rainfall and temperature, but perhaps every whit as potent for the wellbeing of man.

In this ideal representation of the weather experiences there will of necessity be the continuous thread of physical causes which must form the fundamental basis of the pattern. It may be thought

that for such a representation the reader must first be immersed in physical meteorology, but there are certain physical processes which are seen in climate time and again, notably for instance the instability of cold air moving over warmer water and all its consequences in evaporation, cloud, visibility, rain and squalls. True, this is inherent in the concept of Air Masses but it would be a good day for meteorologists if a climatology were produced based from beginning to end on the physical action, and reaction, which are continually going on as day succeeds day, season succeeds season and year succeeds year.

It would be interesting to see what effect such an approach would have on synopticians and climatologists. Perhaps it might have the effect of bringing them together. That would be an inestimable gain, for how often is the forecaster trapped by lack of knowledge of climate. The climatologist and the geographer too, would gain a new interest in a deeper understanding of nature's working.

C.S.D.

Bio-climatic atlas of Israel. By D. Ashbel. Jerusalem (Meteorological Department of the Hebrew University), 1950. 8vo. Pp. 151 + xiv ; 315 figures. $6.

This book is an encyclopaedia, in diagrammatic form, of meteorological data for Israel. The text, printed in both English and Hebrew, runs to only about 1,500 words, whereas the diagrams number over 300.

As may be gathered from its title, it is mainly concerned with the meteorological factors which affect life, and nearly half the volume deals with temperature ; but all the other elements have their quota of diagrams. For pressure, there are specimen synoptic charts of typical conditions and of the situations which gave rise to E. winds, floods, *hamsin* and cold fronts, with specimen barograms and microbarograms. For winds there are monthly roses of wind direction for some 30 stations, isopleths of wind speed, and specimen anemograms ; for rain, charts of the geographical distribution showing the detail that has been added to our knowledge in recent years, charts for wet and dry years, long-period graphs for Jerusalem, hyetograms of intense falls. For relative humidity, dew and evaporation, there are charts of geographical distribution. Insolation receives great emphasis with specially designed diagrams giving the amount of radiation on slopes of different angle and different aspect. The diurnal and seasonal variation of water and soil temperature are illustrated and their variation with depth ; and for air temperature, as well as charts of geographical distribution, there are isopleths of diurnal and seasonal variation (with companion diagrams of relative humidity) and graphs of average daily maximum and minimum temperature, day by day, for over 20 stations in Israel, with specimens of weekly autographic records for over 30. There is also a brief chapter on the thermal structure of the upper air. A supplementary chapter at the end gives information for neighbouring countries. Throughout special attention is given to *hamsin*.

The book gives the impression of vast industry and endless enthusiasm, and for that one is grateful to Dr. Ashbel ; but somehow as one turns the pages, from back to front in conformity with the practice of Israel, upwards and sideways according to the shapes of the diagrams, endeavouring to read the small type of the co-ordinates or to search for scales which are not always there, one is left a little breathless and rather frustrated. There is a wealth of information and the industrious bio-climatologist will probably find all and more than all the meteorological information that he needs ; but he will have to search elsewhere for some of the essential details. There is, for example, no contour chart of the country, no guide to the positions and heights of the stations and no geographical coordinate on many of the charts.

E.E.A.

John Constable's clouds. By Kurt Badt, translated by Stanley Godman. London (Routledge and Kegan Paul), 1950. 8vo. Pp. 102 + ix ; 8 plates. 12*s.* 6*d.*

The title of this book is somewhat misleading, as the first chapter deals with clouds in religion, nature and art, and the next three with the response by Goethe to the classification of cloud forms published by Luke Howard and the influence of these ideas on painters of the Dresden school. The remaining six chapters, dealing mainly with John Constable, set out to show that he gained a new insight into the nature of cloud forms when he discovered Howard's classification ; an insight which made possible the remarkably fine portrayal of clouds in his later work. These chapters also illustrate the impact of scientific ideas on the poets and painters of the Romantic Revival.

The book, which is readable, well produced, and moderately well illustrated, gives the impression that the author has forgotten or never clearly formulated his exact purpose in writing it. A reader studying the development of Constable's painting in the scientific spirit will ask for more facts and above all, more illustrations, but one whose real concern is with the impact of science on art in the early nineteenth century will find here much to interest him.

J.M.C.

Notice of new scientific journal

Journal of Atmospheric and Terrestrial Physics. London (Butterworth-Springer Ltd.). Editor-in-Chief, Sir Edward Appleton, F.R.S. £3. 10*s.* 0*d.* per volume.

"Of making many books there is no end." So said the Preacher about 200 B.C.; what would he have said to-day? We forbear to complete his sentence but quote rather his earlier words, that he "sought to find out acceptable words . . . . even words of truth." That is evidently the aim, in the field of geophysics, of this new journal which has been launched under an editorial advisory board of international constitution, by a distinguished editor-in-chief and a progressive publisher. The international character is well attested in the first number which draws its authors from the four quarters of the globe; that globe which is the laboratory of the geophysical worker whose problems know no national boundaries — or do they, sometimes?

A new journal is not to be welcomed to-day *per se*. It is yet one more volume for the research worker to keep an eye on, that eye which, darting hither and thither, can easily spend too much time away from the laboratory itself. Our own *Quarterly Journal* deals with atmospheric physics though, regrettably in our view, not often with the phenomena of the higher atmospheric levels, and the *Geophysical Supplement* of the Royal Astronomical Society ranges widely, though rather rarely in the geophysical domain. Lately however we have seen the creation of the Journal *Tellus*, with aims the same as those of the new venture, and the broadening of the old *Terrestrial Magnetism and Atmospheric Electricity* into *The Journal of Geophysical Research*. The increasing volume of research in geophysics will probably provide material for all these publications and we wish the latest of them a successful and distinguished career.

The *Journal of Atmospheric and Terrestrial Physics* is to appear bi-monthly at first, and perhaps more frequently later. Papers may be in either English, French or German and there are sections devoted to *Research Notes* and to geophysical events of special interest.

P.A.S.

Recent additions to library

D. Ashbel, *Bioclimatic atlas of Israel.* Meteorological Department of the Hebrew University, Jerusalem, 1950. Pp. vi, 151, viii, 315 figs., $6.

K. Badt, *John Constable's clouds.* Translated from the German by Stanley Godman. Routledge and Kegan Paul Ltd., 1950. Pp. ix, 102, 8 plates. 12*s.* 6*d.*

F. Baur, *Einführung in die Grosswetterkunde.* Dieterich Verlags, Wiesbaden, 1947. Pp. v, 165, iii, 32 figs, 20 tabs. 9 German marks.

F. Baur, *Musterbeispiele europäischer Grosswetterlagen.* Dieterich Verlags, Wiesbaden, 1947. Pp. 36, 25 figs., 2 tabs. 4 German marks.

C. E. P. Brooks, *Climate through the ages.* A study of the climatic factors and their variations. Ernest Benn Limited, Revised edition, 1949. Pp. 395, 39 figs. 21*s.*

L. Janossy, *Cosmic rays.* Oxford University Press, 1950. Pp. 408, 35 figs. 40*s.*

H. and B. S. Jeffreys, *Methods of mathematical physics.* Cambridge University Press, 2nd edition, 1950. Pp. xii, 708. £4. 4*s.*

D. Johnstone and W. P. Cross, *Elements of hydrology.* Ronald Press Co., New York, 1949. Pp. 276. $5.

A. Austin Miller, *Climatology.* Methuen & Co., 7th edition, 1950. Pp. ix, 325, 82 figs. 18*s.*

Ratje Mügge, *Meteorology and physics of the atmosphere.* Fiat Review of German Science, 1939-1946. Office of Military Government for Germany, Field Information Agencies Technical, Wiesbaden, 1948. Pp. viii, 291 tabs. 10 German marks.

J. P. Rothé (and others) *Problemes de Geomagnétisme.* Editions de la Revue d'optique théorique et instrumental Paris, 1950. Pp. 114, figs., tabs.

M. Schwarzbach, *Das Klima der Vorzeit.* Ferdnand Enke Verlag, Stuttgart, 1950. Pp. viii, 211, 70 figs., tabs. No price given.

Tables of scattering functions for spherical particles. United States Dept. of Commerce, National Bureau of Standards, 1948. Pp. xiii, 119, tabs. 45 cents.

C. O. Wisler and E. T. Brater, *Hydrology.* John Wiley, New York (Chapman and Hall), 1949. Pp. 419. 48*s.*

Proceedings at meetings of the Society

Ordinary Meeting, 21 June 1950

The election of the following candidates was confirmed :—

Fellows

Beckinsale, Robert Percy, M.A., Ph.D., School of Geography, Mansfield Road, Oxford.
Coop, Frank, 638 Devonshire Road, Blackpool, Lancs.
Fry, Robert Mason, 26 Clendon Road, Toorak, Victoria, Australia.
Marsh, Dennis Bernard, 113 Poole Road, Bournemouth.
Nolan-Neylan, Sqd/Ldr. Dennis, 99 Sea Place, Worthing, Sussex.
Pathak, Jagdish Chandra, B.Sc., c/o Air India International Ltd., London Airport.
Snodgrass, Donald Claydon, 14 Surrenden Crescent, Brighton 6, Sussex.
Spence, Edward James Walton, 20 Carnanton Road, Walthamstow, E.17.
Wilson, Geoffrey Kenneth, 110 Old Oak Road, London, W.3.

Foreign Members

Mitchell, John Murray, Jnr., Tuxedo, Park, N.Y., U.S.A.
Moore, Paul Raymond, U.S. Weather Bureau, Box 3650, Honolulu, T.H., U.S.A.
Rex, Daniel Ferrell, Lt. Cdr., Lilla Alby Gard, Sundbyberg, Sweden.

Associate

McCormick, Donald Graham, Meteorological Office, 315 Bloor Street West, Toronto 5, Ontario, Canada.

Student Associates

Berry, David Kenneth, 8 Fire Station, Beckenham, Kent.
Morgan, George Rae, 4 Mayfield Terrace, Edinburgh 9.
Pill, John, " Devonia," 32 Kingsholm Road, Southmead, Westbury-on-Trym, Bristol.

The following paper was read :

" Types and Spells of Weather around the year in the British Isles: Annual trends, seasonal structure of the year, singularities."
By H. H. Lamb (see page 393 of this number).

This was followed by a discussion.

Ordinary Meeting, 28 June 1950

The election of the following candidates was confirmed :—

Fellows

Aitken, Charles Frederick, Wadshelf, Nr. Chesterfield, Derbyshire.
Crispin, Paul Ronald, 20 Coburg Buildings, Hardinge Street, London, E.1.
Ezra, Sir Alwyn, " The Cottage," Juhu, Bombay.
Inwood, Albert Ernest, Instr. Lt. R.N., 184 Verdant Lane, Catford, S.E.6.
Jolley, C., 107 Moreland Road, East Coburg, Melbourne, Australia.
Peckover, Peter Albert, B.Sc., Instr. Lt., R.N., 27 Butler Road, Sheldon, Birmingham.

Richards, James Dadds, 94 Talbot Terrace, Scotstounhill, Glasgow, W.4.
Stock, Gordon Derek, 52 Connaught Avenue, Frinton-on-Sea.
Toogood, Kenneth Harrison, 8 Roslin Road, Irby, Wirral, Cheshire.

Foreign Members

Barad, Morton L., Ph.D., General Electric Co., Richland, Washington, U.S.A.
Hiergesell, Valentine, H.B. Instrument Company, 2633 Trenton Avenue, Philadelphia 25, Penna, U.S.A.

Associates

Allen, William Thomas Reid, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Bassett, Gordon Leslie, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Boville, Byron Walter, R.C.A.F. Station, Rockcliffe, Ontario.
Cake, Robert Francois, Met. Office, 315 Bloor Street West, Toronto,5, Ontario.
Cooke, Donald Scott, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Crozier, Clifford Lloyd, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Dunn, Miss Lillian Mary, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Duret, Eugene Louis, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Ellenton, Harold Kenneth, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Fichaud, Raymond Jean-Battiste, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Gee, Gordon Wallace, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Gillies, Donald Kenneth Alan, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Giroux, Charles-Aime, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Hage, Keith Donald, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Hagglund, Melvin Garfield, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Hague, Ross Edgar George, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Holyoke, Donald Lawrence, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Kestenberg, Morris, Main Meteorological Office, Gander Airport, Gander, Newfoundland.
Kwizak, Michael, Met. Office, 315, Bloor Street West, Toronto 5, Ontario.
Macqueen, Kenneth Fraser, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Marshall, Alvin Ernest, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Smith, Gordon, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Tesla, John Ivan, Ph.D., Met. Office, 315 Bloor Street West, Toronto 5, Ontario.
Whiddington, William Barrett, Met. Office, 315 Bloor Street West, Toronto 5, Ontario.

Professor Tor Bergeron (Symons Medallist, 1949) delivered a lecture on "Tropical Hurricanes." The President in congratulating the speaker and thanking him, on behalf of the Society, asked for permission to publish his lecture in the *Quarterly Journal*.

Dr. Charles F. Brooks, (Secretary, American Meteorological Society) in reply to the President's welcome and invitation to address the meeting, said that this was the first meeting of the Society he had ever attended during his 31 years of membership, and he was happy to bring to the Society the good wishes of the American Meteorological Society.

Summer Meeting, 12 *July* 1950

The Summer Meeting of the Society was held at the Central Forecasting Office, Dunstable on 12 July 1950 by courtesy of the Director, Meteorological Office. Some 90 members and their friends were welcomed at 2.30 p.m. by the Director, Sir Nelson K. Johnson, K.C.B. and a reception committee. The party spent a most enjoyable and instructive afternoon. A full account of the meeting was published in the August number of "*Weather*."

Acknowledgment by H. R. Mill of presentation of Hugh Robert Mill Medal and Prize

The President and officers of the Society were arranging to visit Dr. H. R. Mill at his home to make the presentation of the Hugh Robert Mill Medal and Prize to him personally when the news of his death was announced (See *Quarterly Journal*, **76**, p. 356). Mrs. Mill has since found notes (in Dr. Mill's own handwriting) for an acknowledgement of the proposed presentation and has transcribed them. They are given below.

This is a great occasion for me. The honour you have done me is so overpowering that I wish I had the strength, and the facility of speech that were mine when I was engaged in the active work you are now commemorating. In what may well be my last formal address, if this friendly talk can be so styled, my mind goes back to the reception of the first prize I ever received, just 80 years ago. There was then an annual competition for all the schools in the two divisions of Caithness surrounding Thurso and Wick respectively. At the age of nine, I was entered by my first school, to compete in Junior English, and, trembling with shyness, I stood on my first platform and went through a programme before an audience of several hundred people. As I recited two set pieces from Macaulay's *Lays of Ancient Rome*, and Shakespeare, I forgot myself, and became for the moment, first Horatius, and then Shylock, and I was greatly surprised to receive as a prize, a little book, entitled, *Earth's Riches*. It found an echo in my first real book *The Realm of Nature* twenty years later, and it contains a shadow of the obverse of this splendid medal, for on the title page appears a shadowy suggestion of the Tower of the Winds at Athens, the sharp-cut counterpart of which adorns all the medals of the Royal Meteorological Society.

I had a remarkable training in meteorology for I had read Buchan's *Handy Book of Meteorology*, when a boy, with no prospect in life save that of a helpless invalid. However when strength returned, and I had become the " most distinguished " B.Sc. of the University of Edinburgh, in 1883, I got the appointment of Chemist and Physicist to the Scottish Marine Station at Granton on the Firth of Forth. Here, part of my duty was to conduct a second order meteorological station under the direct supervision of Mr. Alexander Buchan himself. Confident of my skill acquired in the Physical Laboratory of the University, I sent in my first large monthly sheet of observations copied out in duplicate, and was summoned to hear Buchan's judgement of my work.

I was quite sure that it was perfect, and got a shock when he said, "I will show you now all the mistakes you have made and how I detected them and to some extent corrected them." And he showed me errors in copying due to carelessness, errors in reading the instruments, errors in addition and division. He produced similar sheets of several adjacent stations, and pointed out that, if all were correct, they confirmed and supported each other, and when one record differed unduly from the others, the exceptional one perhaps showed a 5 degree error in reading. It was the most humiliating and valuable lesson I ever had and but for it, I am pretty sure I should not have been placed in the more pleasantly embarrassing situation in which I find myself at this moment.

I met G. J. Symons in 1886 and gradually got to know him as a genial acquaintance and as the member of various committees on questions of climatology, especially rainfall.

On the death of Symons in 1900, his colleague, and successor, H. Sowerby Wallis, asked me whether I would consider joining him as Joint Director of the *British Rainfall Organization* in Symons's old house, 62 Camden Square. It so happened that I was then very anxious to justify my definition of Geography, as the study of the vertical relief of the solid earth, and the influence of that relief in guiding rainfall distribution. I had been thinking of returning to Oceanography for the detailed study of the effect on moving water, but it came upon me that the influence of surface forms on rainfall would give scope for more detailed study, and moreover, would open a way of earning a modest living by carrying on the Symons tradition. I suggested changes of plans in Symons's methods in the first year, but Wallis would allow no immediate change, and by the end of the second year, I discovered that all Symons's lapses from strict scientific methods brought compensating advantages in dealing single-handed with a vast number of observations, contributed

by a very mixed team of workers, actuated by various motives.

In 1903 Wallis retired after a breakdown of health, and as sole Director I was able gradually to substitute research largely by cartographic methods, familiar in Geographical work, for the mere statistical groupings of unrelated observations. Thus I tried to make every detailed study I was commissioned to make for Water reservoirs, for Public Bodies, like Gairloch Survey and the Thames Valley Authority, fit into a common plan, with the definite purpose of getting a detailed map of the distribution of rainfall on the average of many years, but also to work out detailed maps of average rain days and groups of monthly periods, when prevailing winds from various directions present a considerable problem.

I had gone far with this work when a stop was put to it by the complete breakdown of my eyesight at the end of 1912. I took eighteen months of complete rest, travelling round the world, with a long stay in New Zealand, and I returned in June 1914 ready to resign, and retire. My arrangements for retiring from British Rainfall were blown to pieces by the outbreak of the First World War. All the assistants who could pass the health tests either joined up, or were called up, so that only Mr. Carle Salter, my chief assistant with a poor health record, and Mr. Lamport, more than 70 years of age, were left. The 4 years of the War were a nightmare, but working through my wife's eyes I kept control and did succeed in keeping the Organization going. In 1919, the Trustees, with my full approval, made over the collection of Rainfall data and the continuous publication of results to the Government, as represented by the Meteorological Office.

The surviving members of the staff were taken over by the Meteorological Office and the old Symons tradition was carried on through Dr. John Glasspoole, who has continued to give an annual report early in January summarising the results of the previous year. The old house in Camden Square and the small Endowment Fund for its upkeep were made over to the Royal Meteorological Society, who accepted an obligation to keep the long record of meteorological observation in perpetuity, an obligation which the Society has observed with perfect fidelity.

The Meteorological Office also kept up the collection and preparation of the annual work of the observers. Publication stopped for a time, but is now being continued, so that that gap will eventually be bridged.

I owe it to the Society that I was provided with the welcome opportunity of diverting my mind from the frequent bombing of Dormans Park in the preparation of an autobiography now in the press. The idea sprang from a request by Sir Gilbert Walker, a former President of the Society, on my 80th birthday in 1941, which was also my fiftieth year as a Fellow of the Society, to write some reminiscences of that period for the Society's Journal, afterwards expanded to form the chapter on British Rainfall, which in company with other chapters dealing with my life-interest in other branches of the study of water in Nature, form the central motive of all my studies and researches.

I take this Medal as a reward for the persistence with which I follow the far more important work of my successors, after my own working days are over. I take it as a very great addition to the honour you have done me to receive this medal from your own hand today.

Obituary

Dr. J. R. ASHWORTH

Cultural life in north-western England has been impoverished by the loss of the Lancashire scientist Dr. James Reginald Ashworth, who died at Rochdale on 9 July 1950 — the day after he had entered his ninetieth year. Trained for the scholastic profession, Ashworth was appointed teacher in physics at the Rochdale Technical School not long after its foundation in 1891. This post he occupied with conspicuous success for more than one-third of a century. When he joined the staff in 1893 only twenty-three students were attending the physics and electrical engineering courses ; by the time of his retirement in 1928 the number had increased to three hundred. But Dr. Ashworth's chief claim to Lancastrian remembrance lay in his remarkable achievement of sixty-five years' continuous service as honorary secretary of the Rochdale Literary and Scientific Society. It is said to have been largely through his devoted efforts that the society contrived to keep its flag flying through both the World Wars. From 1917 to 1919 he added presidential duties to those of secretaryship. For the occasion of the society's fiftieth anniversary celebrations in 1928 the Hon. John Collier was commissioned to paint Dr. Ashworth's portrait, and this was presented to him at a special jubilee meeting. By holding unbroken membership of the local Public Libraries, Art Gallery and Museum Committee over a period of sixty-three years Ashworth set up a record unrivalled in the municipal history of Rochdale. He had also accepted latterly the position of curator to the Manchester Literary and Philosophical Society.

Ashworth's abilities as a physicist won recognition in a wider scientific sphere than that of Lancashire. He had long been known as a specialist in magnetism, with various aspects of which subject he dealt in a number of books and pamphlets. Shortly before the outbreak of the Second World War he was honoured by an invitation to address a conference on magnetism organised at Strasbourg by the French Central Council of Scientific Research. During his later years he gave much attention to the study of ultra-violet rays in their relation to the solar cycle, and also interested himself in the measurement of atmospheric pollution. For the purposes of this work he supplemented the established instrumental equipment by apparatus of his own devising, such as autographic ultra-violet meters and pollution gauges for recording the amount of impurity borne horizontally by the winds. Ashworth contributed frequently to the literature of these and kindred physical subjects. His monograph *Smoke and the Atmosphere* (Manchester University Press, 1933) attracted considerable attention from scientists and municipal authorities. Within the last few months he published through the Liverpool University Press a small book concerned with the bearing of sunspot frequency on ultra-violet radiation. Of his many papers and articles on these two subjects several appeared either in this *Journal* or in *Weather*. The aim of his first communication to our Society was to show that a slight deficiency of rainfall at Rochdale on Sundays as compared with week-days could be attributed to the smaller Sunday emission of smoke and hot gases from the borough's mill chimneys. Ashworth's observational methods and derived results sometimes came in for severe criticism, but he was in no way deterred by this, and in defence of his findings he did not hesitate to cross swords with the mighty. His election into the Royal Meteorological Society took place on 21 November 1934. He also held fellowship in the Physical Society.

E.L.H.

Major A. F. BOWKER, Assoc.M.Inst.C.E., F.R.G.S., F.G.S., F.Z.S.L.

The very small remaining company of Fellows who were elected into this Society before the close of the 19th century suffered depletion on 12 June 1950 by the death in his 84th year of Arthur Frank Bowker. A Londoner by birth, Bowker was educated at Winchester and University College School and then served an engineering apprenticeship at Battersea, where he worked for a time in the same shop as John Burns. He qualified on both the mechanical and civil sides of the profession, eventually specialising as a water engineer. From early youth he was keenly interested in geography, and while still at school he won a gold medal offered by the Royal Geographical Society for proficiency in map-making. Later he contributed to the proceedings of that Society accounts of journeys which he twice made across Africa on foot and also of his travels in Asia. As a young man Bowker took part in a Canadian geological expedition to the Yukon and in successful prospecting for Klondike gold. Wherever he went the weather always held fascination for him. In England he made contributions to climatological study by keeping records of rainfall, temperature and other elements at his successive places of residence in Kent. He maintained these observations long after he had given up professional work and until failing eyesight at an advanced age prevented him from reading his instruments. His election into the Royal Meteorological Society, which benefits under his will, took place on 16 March 1892. Bowker held the rank of major in the Territorial Army. At one period, when well on in life, he coupled simultaneously the rôles of regimental officer at Woolwich

and chief engineer at a Kent waterworks — each a scheduled " whole-time " occupation. Resultant overwork led to an undermining of his health from which he never fully recovered. A zealous high churchman, Bowker gave generously of his time and means to promoting the spiritual welfare of his fellows. He founded at his own expense a religious institution known as the Society of Retreat Conductors. Much of the information contained in this notice has been made available to us through the courtesy of Major Bowker's friend the Reverend P. G. Bacon.

E.L.H.

Mr. A. STOCKS, B.Sc.

Mr. Arthur Stocks, whose death occurred on 26 April 1950, had been a Fellow of this Society since 19 March 1919. He was born near Bradford and graduated B.Sc. in 1900 at the Yorkshire College, now the University of Leeds. In 1904 he came south, initially as a staff member of the Pupil Teachers' Centre at Portsmouth. Soon afterwards he was appointed geography master at the Portsmouth Southern Secondary School. Here he remained until his retirement in 1945, except for a period of service as meteorological officer at the Beachy Head Royal Naval Air Station during the 1914-18 war. This fostered an early enthusiasm for meteorology which never lapsed and which stimulated him to use his opportunities for encouraging interest in the science among the hundreds of pupils who passed through his classes. In 1936 Mr. Stocks published a valuable 40-year summary of the Portsmouth weather records. Since the end of the 1939-45 war he had prepared much of the material for extending this analytical study to cover half a century, but death overtook him before he could fulfil his intention. Mr. Stocks was a founder member and one-time president of the Portsmouth Society of Yorkshiremen ; he was also prime mover in the formation of the Yorkshire Nomads' Cricket Club, established under the auspices of that body.

E.L.H.

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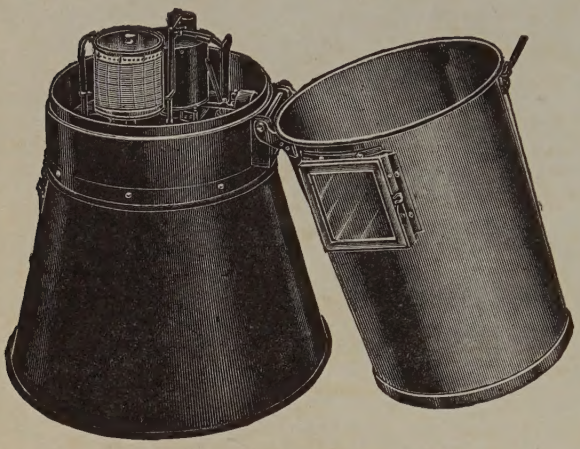

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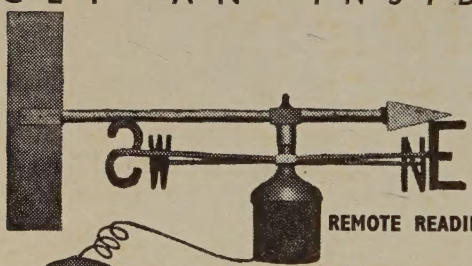

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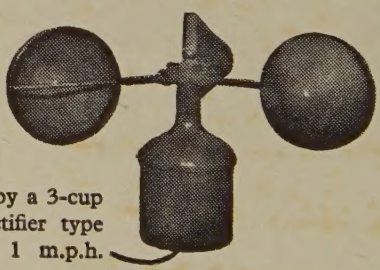

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